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F. A. TSANDER AND MODERN COSMONAUTICS

Yu. S. Voronkov et al.

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16. Abstract This collection is dedicated to the analysis of the scientific heritage of one of the pioneers of rocket and space science and technology, F. A. Tsander. The development of the ideas of F. A. Tsander and their realization in modern astronautics are traced in such areas as astrodynamics, the theory and design of motors and space vehicles, life support systems and astrobotanics. Considerable attention is given to analysis of the role and significance of the works of F. A. Tsander in the history of rocket and space science and technology. The collection is intended for specialists in the area of aviation and rocket-space science and technology, as well as readers interested in problems of the development of aviation and astronautics.

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FOREWORD

The name of Fridrikh Arturovich Tsander -- that remarkable Soviet scientist and engineer, interplanetary flight enthusiast -- occupies a leading position in the history of domestic and indeed world rocket-space science and technology. The tendency to understand and illuminate the rich scientific heritage of F. A. Tsander, to study his creative methods, to trace the development of his ideas in modern science and technology is quite justified and proper.

One of the forms of activity of the Commission of the Academy of Sciences USSR for the Development of the Scientific Heritage of F. A. Tsander, facilitating coordination of efforts and attracting a broader range of researchers interested both in the development of the scientific heritage of F. A. Tsander and in the development of his ideas in modern rocket and space science and technology, is to conduct traditional scientific readings devoted to F. A. Tsander. The first such readings were held in Riga 12-15 May 1970, the second -- in Leningrad 19-22 May 1972, the third -- in Moscow 26-29 March 1974.

From readings to readings, the number of participants has increased, as well as the number of reports and messages. At the latest such gathering, the plenary sessions and sessions of the individual sections of which involved the participation of over 700 specialists from various cities of the country, more than 50 scientific reports and messages were heard.

The need has arisen to select the most interesting facets of that which has been discussed at all of the readings held to date. This is the purpose of the present collection.

In discussing the problem of the structure of the collection, the editorial group decided to follow the traditions which have been built up in publishing the works of previous readings. This tradition consists in that the scientific heritage of F. A. Tsander is varied, but combined by its unity of purpose. Three main trends can be noted in his activity: the development of theoretical problems of astronautics, work on the creation of the principles of the theory of design and construction of space flight vehicles and reaction engines, investigations related to the development of individual systems of spaceships, particularly work on the creation of life-support systems.

Therefore, the articles selected by the editors for this collection are grouped in just this way. Naturally, there is a special section of articles dedicated to the analysis of the scientific creativity of F. A. Tsander.

Section I was prepared under the leadership of Professor L. S. Dushkin and Doctor of Technical Sciences Ye. K. Moshkin, Section II -- under the leadership of Doctor of Technical Sciences T. M. Mel'kumov and Doctor of Technical Sciences Ye. S. Shchetinkov, Section III -- under the leadership of Corresponding Member of the Academy of Sciences B. V. Raushenbakh, Section IV -- under the leadership of Corresponding Member of the Academy of Sciences USSR O. G. Gazenko.

As appendices, the book includes: "A Bibliography of Works on the Investigation of the Creativity of F. A. Tsander," prepared by B. L. Belov, a Scientific Fellow of the Institute of History of the Natural Sciences and Technology, and "Basic Materials on the Investigations of F. A. Tsander in the Area of Rocket-Space Science and Technology Stored in the Archives of the Academy of Sciences USSR," prepared by Scientific Fellow of the Archivesof the Academy of Sciences USSR L. G. Samokhvalova, with the participation of B. L. Belov and the daughter of the scientist -- Astra Fridrikhovna Tsander.

The editors hope that this collection may be useful to all those interested in the personality of F. A. Tsander, his activity, problems and the achievements of modern rocket and space science and technology.

The Editors

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I

INVESTIGATION OF THE SCIENTIFIC CREATIVITY OF F. A. TSANDER

SOME ASPECTS OF THE STUDY OF THE SCIENTIFIC HERITAGE OF F. A. TSANDER

Yu. S. Voronkov

We believe that there are two main interrelated, or more precisely combined, trends in the problem of the study of the scientific heritage of F. A. Tsander, as, incidently, is the case with the heritage of any other scientist or engineer who has left a significant trail in the development of some given area of science or technology. /5*

The first trend is analysis of the element ("brick") of the process, which is usually called the logic of development of the corresponding branch of knowledge. The second trend is analysis of the role and significance in the logic of development of the corresponding branch of science both of the element and of its creator. Both of these trends are multifaceted and have multiple aspects, but the final purpose must be the reconstruction of a single historic process, leading finally to the gaining of new knowledge.

We have not set ourselves the task of giving a full selection of all aspects and their characteristics in the development of the scientific heritage of F. A. Tsander. We will limit ourselves to a general statement of the problem and analysis of the individual methodological approaches suitable for its solution.

In analyzing the current state of development of the scientific heritage of F. A. Tsander (using the available materials), we can somewhat arbitrarily distinguish three groups characterizing the basic trends of this development.

1. The publication of originals of individual works and materials of F. A. Tsander. This trend is one method of revealing and systematizing reliable factual material and therefore is of great value as material for investigation but is not in itself investigation. The "absolute" value of such works at the present time is slight, in contrast to, let us say, the 1930's, when this type of publication was practically an independent goal in itself [1].

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*Numbers in the margin indicate pagination in the foreign text.

2. Analysis of individual developments of F. A. Tsander both from the standpoint of restoration of their maximum completeness and reliability, and from the standpoint of evaluating their significance in the development of rocket-space science and technology.

3. Attempts to illuminate the creative path followed by F. A. Tsander.

We must note that these trends of development of the scientific heritage of F. A. Tsander (naturally, we are speaking of the second and third), with all of their relative sparcity, are developing in a sense into their own rather narrow specialty.

It seems to us that we cannot now limit ourselves to analysis of individual developments of Tsander or individual aspects of his activity. Taken in and of themselves, they cannot be understood and properly evaluated. It is also useless to evaluate them solely from the standpoint of today, seeking in them the "seeds" of various ideas currently in use. /6

For example, let us analyze the widely known plan of Tsander for "an aeroplane equipped with a rocket" [2] from this standpoint.

Analyzing this plan in isolation, without considering the level of science in this area both here in our country and abroad, without considering the personality of Tsander himself, it is impossible to estimate its significance.

Naturally, all of its elements were known before Tsander. Attempts to compare this plan with modern multistage rockets show the immaturity of the design ideas of Tsander. (This is true both of the design of the glider itself and of the use of the propeller-motor installation, etc.) Furthermore, F. A. Tsander himself saw the individual specific technical weaknesses of his suggestions. For example, concerning the design of the glider in the early 20's, he wrote: "...the biplane was taken as an example (our italics -- Yu. V.) of the airplane to be developed, but aeroplanes of various systems might be used, or the body of the rocket might be used as a supporting surface " [3].

It is more expedient to evaluate this project as an answer to the question: "Was the decision of F. A. Tsander the most suitable for the situation, was it the only decision possible?"

We must here emphasize that engineering development, in contrast to fundamental theoretical research in its pure form, in the stage of solution of problems which are soluble in principle, is generally speaking not realized. Thus, in drawing a straight line between the past and the present, we not only simplify the process of development, but also and actually

distort it, since an approach of this sort would evaluate almost all of the developments of F. A. Tsander as at least naive.

As an example of this naivete, we might mention the erroneous estimates by F. A. Tsander as to the future dates of space flights: "Thus, we have so closely approached the possibility of escape from the terrestrial atmosphere, that we need but perform a few experiments on the type of interplanetary space vehicle here suggested, spending comparatively little money, and the idea of flight to other planets will be a reality" [4, p. 10].

However, this "naivete" is not a result of a primitive understanding of the problem. The simplification of the path which had to be followed to solve the problem, the underestimation of the time required, were results of the strong belief of F. A. Tsander in the importance and correctness of the path which he has selected. (Suffice it to recall his words, famous among his colleagues, "To Mars! To Mars!")

Returning to Tsander's "aeroplane equipped with a rocket," we must note that a tremendous range of both theoretical and practical research lies between this plan by F. A. Tsander and today's concepts concerning such designs.

Without absolutizing the knowledge gained experimentally, we must state that it does have a role to play in technology. Until experimental results are produced, ideas need only be noncontradictory on the surface. (For example, the idea of F. A. Tsander of using no longer necessary metal parts of a space vehicle as fuel for its continued flight.)

In evaluating the work of F. A. Tsander, we must keep in /7
mind that he but began the engineering development of the problems of rocket-space technology. Therefore we must evaluate not so much the maturity of his solution of a problem as the optimality of its statement. In the case of the same "aeroplane equipped with a rocket," consideration of the entire context of the historic moment shows that Tsander made a basic and in its way revolutionary transformation in our ideas concerning the methods of achieving space flight. The old ideas, the sum of knowledge gained, was supplemented by quite basically new knowledge which, on the one hand, eliminated the contradictions resulting from the colossal weight of a rocket, the acceleration during the launch and the use of the parachute for descent [5, pp. 2-3], and, on the other hand, provided the "possibility of using the tremendous material accumulated by aviation for interplanetary voyages" [5, p. 1].

We can draw yet another important conclusion from the example we have presented: even analysis of a fact (as a result of certain actions) is not a goal in itself, and given the specific historic reality does not allow us to produce a sufficiently objective historic reconstruction.

Any attempt to integrate results leads to the need to consider the creative processes preceding the production of the results, since without this there could have been no historic process, and it is the recreation of this historic process which is our task.

Therefore, the evaluation of the contribution of F. A. Tsander to the development of rocket-space technology is impossible without recreating his creative personality. This task is at the present time quite an important one.

"The history of science," write academician B. M. Kedrov, "usually involves recording the thoughts of a scientist in their final phase, after a discovery has been made and more or less perfected. The task is to represent his ongoing work at the moment of making of the scientific discovery as a living and moving process. Consequently, the task is as follows: to restore, i.e., bring back to life, the creative thought of a scientist who has long since died, the initial materials for this operation consisting of scattered documents and information which he has left behind, partially known and, possibly, even published, partially not yet found. Is such a task possible? If so, it is possible to restore the psychological aspect of the perfection of a given discovery and to penetrate by looking mentally into the creative laboratory of the scientist as if he were alive today and we ourselves were present during the making of the discovery. But can this be achieved?" [6, pp. 36-37].

The performance of this task on the example of a man like F. A. Tsander allows us to "algorithmize" engineering developments (naturally, we do not mean the generation of some set of formal rules with which the creative process could be controlled). The form of the solution of this problem might be the development of a scientific biography of F. A. Tsander.

The purpose of such a decision has been previously mentioned. The object of investigation, obviously, must be the creative personality of F. A. Tsander himself, the process and results of his functioning. The basic obstacle in the path of achieving this goal is the method, or more correctly, the methods of investigation.

The increase in the number of methods by which the creative personality is studied, the increase in the sum of knowledge concerning the creative personality in general, by no means makes the task of studying, particularly of "reconstructing" a creative personality simpler. On the contrary, the contradiction between increasing and fractionation of the aspects characterizing the creative personality become still greater, and the difficulty of /8
reducing these aspects to a single unit increases.

Thus, the question as to how we should transform the personality of F. A. Tsander and the results of his activity from a set of units to a unity of sets as yet remains open. However, it does seem desirable to note some of what we consider to be the most important trends in the development of the scientific biography of F. A. Tsander.

Initially, it seems to us, we must determine the conditions under which the creative personality of F. A. Tsander grew and developed. These general conditions, obviously, can be divided into two main interrelated groups -- external and internal. The external conditions include everything which acted upon F. A. Tsander and transformed him from his early childhood to the end of his life (the social environment, books, system of education, level of development of science and technology, etc.). Internal conditions include the entire complex of traits which somehow characterize the creative personality today (the ability to receive and accumulate knowledge, the ability to generate new knowledge, motivation toward creativity, methods of production and affirming new knowledge, etc.).

We must consider here, as we noted earlier, that in addition to the logical aspects, which can be formalized in analysis for purposes of historical reconstruction, there are a number of aspects which cannot at present be formalized -- those related primarily to the analysis of the actual creativity of F. A. Tsander. Under these conditions, obviously, we must use methods characteristic for the description of the artistic method of understanding of reality. Is this sort of "willfulness" permissible"?

The question is unusually complex. As we know, the essence (or one of the determining peculiarities) of science consists in the establishment of objective relationships between two or more experiments or phenomena which can be reproduced and tested. This leads us back to the necessity of formalization of the method of investigation.

However, if, in developing the scientific heritage of F. A. Tsander, we satisfy ourselves with mere formalized (for a given moment in time) methods of investigation, we produce a colorless and incomplete, though objective, picture of the process being studied.

In conclusions, let us emphasize once more that the final purpose of the development of the scientific heritage of F. A. Tsander, in our opinion, is to recreate a single historic process, harmonically including the results of the activity of F. A. Tsander and the process of production of these results, considering both external conditions predetermining and forming the process and, naturally, its results, both internal, making possible

the existence of the process, and its results.

Only this unity in the final analysis will allow us objectively and vitally to show the role and knowledge both of F. A. Tsander himself and the results of his activity in the development of rocket-space technology.

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THE RIGA PERIOD IN THE LIFE AND ACTIVITY OF F. A. TSANDER (1887-1915)

Ya. P. Stradyn'

Fridrikh Arturovich Tsander lived a short but brilliant life of only 45 years. His most fruitful, creative period was the time he spent in Moscow during the great years of the revolution and the post-revolutionary rise, when Tsander became a pioneer in practical rocket building in our country and set forth a number of remarkable ideas, far ahead of his time, concerning the possibility of achieving interplanetary flight. It is due to the works of this period that the name of Tsander has entered the history of science and technology. /9

However, for the first 28 years, or almost two-thirds, of his life, Tsander lived in Riga. Here he was born, here received his engineering and scientific education, here his first ideas and plans for interplanetary flights were born. This is why we, residents of Riga, patriots of our city, as well as all of the investigators of the creative heritage of Tsander, are greatly interested in the Riga years, the years of formation of his personality and of his first studies. This is why Riga was selected as the location of the first Tsander readings.

The documentary materials for the recreation of this period consist of the materials in the archives of Riga and Moscow, the statements of Tsander himself, contained in his various books, articles, reports and summaries, as well as the recollections of his contemporaries. Of these we note first of all the touching recollections of the sister of the inventor, Margarita Yurgenson-Tsander, published in [1].

The Latvian historian of aviation technology D. Ya. Zil'manovich has done great work on the systematization of materials on the biography and early period of creativity of Tsander [2]. The Riga period has also been partially discussed in other materials concerning Tsander [3-6]. Therefore, we shall recall here the basic chronological data related to this period in the life of Tsander.

Fridrikh Arturovich was born on 23 August 1887 in Riga into the family of a Doctor of Medicine, Artur Tsander. In 1905, he completed the Riga Practical School and entered Riga Polytechnical Institute (RPI), the Division of Mechanics. In November of that same year of 1905, so important in the history of Latvia, in response to the demands of the administration "not to place political activity before academic activity," Tsander requested that he be allowed to resign from the Institute. He traveled

to Danzig and studied in the Higher Technical School there for a year and a half. In 1907, he resumed his studies at RPI, and on 31 June 1914, one day before the beginning of the first World War, he was graduated with distinction. In August of 1914, he became an engineer at "Provodnik" a large Riga rubber plant, and exactly one year later, in August of 1915, due to the approach of the German forces toward Riga, he was evacuated to Moscow together with the plant. Tsander never returned to Riga, all of his future activity occurring in Moscow. These are the basic facts concerning the Riga period of the life of Tsander.

First of all, let us study the question of how the environment in Riga, the intellectual, technical, cultural and social atmosphere of Riga, influenced the development of Tsander as an engineer, inventor and enthusiast of interplanetary flight. As we know, the most important conditions -- the environment, education, the flow of impressions -- may facilitate the development /10
of natural talent, but may also inhibit this development, changing the direction of interests. How potential talent could be discovered, selected, predicted in development -- in the early 20th Century another outstanding citizen of Riga, the chemist and philosopher of science, Wilhelm Ostwald (1853-1932) thought a great deal about these questions. In one of his works, he noted that "more potentially great persons are born than actually achieve development, a result of the harmful influence which suppresses many possible geniuses... We have no means," Ostwald wrote, "of counting the number of fallen geniuses, but we would be horrified if we knew how mankind in this case damages itself" [7, p. 289]. In this same work, Ostwald writes that "...one sign of talented persons is that they are never satisfied with the scientific materials which are taught them according to the plan... A man with moderate abilities loses time in perceiving scientific material and simply retaining it, the outstanding man, even in youth, is distinguished by his ability and need to develop his own independent views and work" [7, p. 35]. Ostwald properly considered that early development, the beginning of creativity in youth is one of the distinguishing features of talent. It is characteristic of an outstanding personality that he early in life finds the problem of his life and does not shrink from it.

The personality of Tsander was formed in those very years when Ostwald set forth these thoughts in his remarkable books "Investors and Discoverers," and "Great People." These books must have been read by the young Tsander.

The specific biographic material on Tsander states clearly that the future engineer met that criterion of potential talent which Ostwald considered decisive: early maturity, the tendency to seek out knowledge outside the school, attraction to books, a search for mature friends, expediency of interests, creative work, authority, even leadership among his young comrades.

As to the question whether the environment in Riga aided or suppressed the development of Tsander's talent, there can be but one answer -- it aided it.

In the early biography of Tsander we clearly see the main positive forces: the influence of his family; his school; contact with scientists of Riga; the influence of industrial Riga -- one of the centers of technical progress in Russia; the influence of the democratic and revolutionary surroundings.

The father of the scientist, Artur Tsander (1854-1917), was a physician well known in the city [8]. Old timers recall his professional mastery, his humanity, the breadth of his views [2, pp. 34-37]. Furthermore, he was a science fan, a science dilettante, like few others in Riga. They were drawn together by the very active Riga Society of Natural Scientists (founded in 1845), a leader for its time. Tsander the elder actually led the Natural Science Department of the Cathedral Museum (now the Museum of Nature of the Latvian SSR), collecting for it rare and exotic animals and birds. He was vitally interested in astronomy and the then-nascent science of aviation, collecting a large library and reading science fiction. A. Tsander drew his son into everything with which he was occupied. As F. Tsander recalls, it was the participation in scientific studies of his father, constant visits to his museum, reading of books from his father's library which stimulated his fantasy and interest in independent scientific research. In the first version of the foreword to his book "Flights to Other Planets and to the Moon," Tsander wrote that it was the stories of his father concerning /11
the stars, the planets, his fantasy of the possible animal world on these planets, his stories of the flights of O. Lilienthal, as well as his father's love of toy rockets which "...stimulated in me at an early age the question of whether it might not be possible for me personnally to fly to the other planets. This thought never left me. Early on, I began to learn the constellations from star maps and memorize their outlines" [5, p. 56]. These were his first childhood impressions, and later, during his youth, when Tsander began his own independent research, his father fully supported the initiative of his son, encouraging his scientific tendencies which doubtless was an important factor in the life of Tsander.

What influence did school have on Tsander? The Riga Practical School where Fridrikh studied was at that time distinguished by the good education it provided. Many outstanding people were educated within these walls: the motion picture director S. Eisenstein, the first President of the Academy of Sciences, Latvian SSR A. Lein'sh, the well-known forester, Academician of the Academy of Sciences Latvian SSR A. I. Kalnin'sh, the artist S. Mikhoels and others [2, p. 52]. Here in 1904 the young Tsander first learned of the works of Tsiolkovskiy. "During the last year of school," Tsander writes, "before the winter holidays our

cosmography teacher read us a portion of an article written by K. E. Tsiolkovskiy in 1903 under the title 'The Study of Space Using Reaction Devices.' (The belief of the greatly respected K. E. Tsiolkovskiy that his work was ignored for 20 years was thus not quite accurate.)" [5, pp. 56-57]. Great credit in this must go to an ordinary Riga teacher of history and cosmography named Vesberg, who familiarized his students with the article of Tsiolkovskiy, with an article which was so far ahead of its time that official science virtually ignored it both in Russia and abroad. But for the young Tsander it was doubtless one of the forces behind his active interest in rocket engineering as a means of conquering cosmic space.

Of decisive influence in the formation of Tsander as an engineer was the time he spent within the walls of the Riga Polytechnical Institute (founded in 1862). This was the oldest polytechnical institute in Tsarist Russia, one of the leading centers of technical education in the country [9, 10]. Many of the future great activists of science and technology came from here; at various times, great scientists taught here. We have already met one professor of RPI, the future Nobel Prize Laureate W. Ostwald. His popular textbook "Schule der Chemie" was the first text used by Tsander, with which he conducted chemical experiments even before he entered the Institute. One of Ostwalds students was academician of the Peterburg Academy of Sciences, later Honored Academician of the Academy of Sciences USSR Paul Walden (1863-1957), a great and multifaceted chemist with a European name, an outstanding lector and popularizer of science, a professor of RPI [11]. Tsander heard his lectures, read his articles, outstanding in form and content. Tsander might have been influenced by another of his teachers, the well-known specialist on combustion chambers and heat engineering, Professor K. Blacher (1867-1939). A technologist with innovative ideas, he spoke out for the idea, not commonly held at that time, that the creation of complex technological processes should be modeled in scientific laboratories, not merely solved on the basis of experiments by practical engineers [12]. The teachers of Tsander included the great mathematician Pirs Bol' (1865-1921), whose basic works on celestial mechanics, the theory of near-periodic functions, etc. are only today fully being understood [13]. Another teacher at RPI was one of the pioneers of aviation engine building in Russia, Teodor Kalep (1866-1913), whose scien- /12
tific biography has drawn the attention of historians of technology [14]. We can note other RPI professors with whom Tsander came or might have come in contact: the Dean of the Mechanical Division, the great shipbuilder C. Clark (1867-1842), the expert on reinforced concrete structures V. M. Keldysh (1878-1965), the climatologist Rudol'f Meyer (1880-1966), the metallurgist, later Vice President of the Academy of Sciences USSR, E. V. Britsis (1877-1953) and others. These men were all truly outstanding engineers and scientists who, doubtless, were capable of giving the young Tsander a very solid scientific and engineering background.

We must note the high scientific level of the teaching of chemistry at RPI [15]. Tsander doubtless received excellent training in this important area, which was later favorably reflected in the development of many of his ideas (on chemical thermodynamics, the combustion of metal fuels, etc.). Still more important for the young Tsander was the interest which his teachers, particularly T. Kalep, manifested in the then new science of aviation. It is not by chance that an honored member of RPI, on the occasion of the 50th Anniversary of the Institute, was named the "Father of Russian Aviation,": Professon N. Ye. Zhukovskiy.

We must commend the administration and instructors of the Institute for their support of the initiative of their students. This support was manifested, for example, in the cooperation which was given the first Students' Society for Aviation and Flight Technology at RPI. Organized in 1908, at the very dawn of the era of aviation, with the active participation of F. A. Tsander, this Society did a great deal to popularize the principles, achievements and prospects of aviation. The members of the Society read reports, constructed aviation models and gliders. The Society organized the first exhibit of aircraft in Riga where, in addition to model airplanes and gliders, the Wright aircraft, brought in from Berlin, was also on display. At the opening of the exhibit, held in March of 1910, the governor of Lifland and other officials, the Director and professors of RPI were present [2, p. 148]. The organizers of the exhibit, however, were students, the same club which is now considered the cradle of the Students' Scientific Society of RPI. Let us think about that for a moment. In our, Soviet time, this would be a normal phenomena. However, under the regime of the Tsar, when the organization of any students' society, even those quite remote from politics, was looked upon with suspicion, the administration of the Institute must have been both brave and understanding to develop and support the initiative of the students.

Let us further look for a moment at the influence which industrial Riga had on Tsander. In Tsarist Russia, Riga was doubtless one of the primary centers of scientific and technical progress. We can rightfully be proud of the successes of our Latvian Republic in Socialist industrialization, in the creation of modern industry, which has far exceeded the level of prerevolutionary bourgeois Latvia and the level of the time of Tsarist Russia. Under the conditions of Tsarist Russia, Riga occupied a quite exceptional position, with a significant share in the industry and technology of Russia. At that time, the great centers of Socialist industry and technology such as Novosibirsk, Kharkov, Sverdlovsk, Kuybyshev, Kazan', Saratov, Minsk and Baku, created during the Soviet era, had not yet begun their activity. Heavy industry of Tsarist Russia was primarily concentrated in Moscow, Peterburg, Odessa and other cities of Russia. Whereas now Riga

ranks 25th in population among the cities of the USSR, in Tsander's day Riga was the fifth largest city in Russia after Peterburg, Moscow, Odessa and Lodca. Riga was then the largest port in Tsarist Russia (the largest export harbor and the second largest import harbor after Peterburg) [16, p. 153]. This situation of Riga had developed due to its historical situation -- first of all the dependence of Tsarist Russia on the more developed capitalist countries, particularly Germany, as concerns the export and import of raw materials, semifinished goods and machinery. This stimulated the development of the industry of Riga. Many of the leading technical ideas of Europe reached Riga before they reached other cities in Tsarist Russia. We can cite many examples from the history of domestic science and technology in the 19th and 20th centuries, confirming the thesis of the transit role of the Baltic area in the development of Russian-western scientific and technical contacts, its role as a pioneer in technical innovation [17]. The higher level of capitalist development, the proximity to the developed countries of Europe, the intensive transit trade all made the Baltic border a leader in Tsarist Russia. /13

As one of the largest industrial cities and the center of training of engineers, with a qualified contingent of machine-building workers, Riga should have and indeed did become one of the main centers of aviation, railroad, bicycle and motor vehicle construction in Russia. The first aviation motors and airplanes in Russia were constructed at Riga's "Motor" Plant under the leadership of the Chief Engineer of this Plant, T. Kalep, whom we have already mentioned, beginning in 1909-1910. Beginning also in 1910, the Russian-Baltic Car Plant began the production of aircraft. At this plant a base was created for the planning of the first domestic multiengine aircraft -- the prototypes of the "Russkiy Vityaz'" and "Il'ya Muromets" by the well-known aviation designer I. Sikorskiy [9, pp. 98, 99]. However, production of these aircraft was begun in Peterburg at the "Russobalt" affiliate, where the entire aviation department of the Plant was transferred from Riga in 1913. "Motor" Plant was located quite close to Tsander's home in Zadvin'ya, and the young student, doing practical work in the Department of Construction of Airplanes at the Plant, spent all his free time there. Almost right next door was the Hippodrome of "Solitude" Field, a large open space next to "Imanta" Station, where on 6 July 1910 Riga's first successful airplane flight occurred.

This contact with aviation technology at "Motor" Plant had a deep influence on the engineering thought of Tsander, directing his interests not toward theoretical, but toward direct engineering work in the area of space technology, which was manifested in all his further work, for example in the creation of the winged interplanetary ship.

Finally, Tsander's association with democratic Riga, revolutionary Riga. Fridrikh Tsander was in contact with revolutionary

youth in both elementary and secondary school. In one questionnaire, Tsander wrote that he had sympathized with the Communists since 1911 [6, p. 17]. There are also indications, though not quite definite, that in 1905 he himself was briefly arrested on a political charge [2, p. 89]. Tsander himself, however, was no revolutionary: from childhood he had been so absorbed in science and technology that he could be concerned with nothing else. However, he was a progressively inclined person, and this weltanschauung came to him from his family. His father, Artur Tsander, as we have said, was distinguished by his democracy and breadth of views. He assisted his neighbors, the Dubel'shteyn family, taking their older son Yekab as an apprentice (1883-1907); at one time, he even lived with the Tsander family. During the revolution of 1905, Yekab Dubel'-shteyn proved himself a capable leader of the social democrat warriors, organizing daring assaults on the prefecture and the jail. He was a victim of the counterrevolutionary terror -- he was shot in 1907 after being sentenced by a field court martial. /14

It was not by chance that after the October Revolution and the subsequent wresting of the Baltic area from Russia, Tsander did not follow the example of the overwhelming majority of his countrymen -- Baltic Germans, did not return to his homeland, but rather remained in Soviet Russia -- the homeland of October, where he became a great inventor. The family of Tsander was split, since the rest of its members remained in Latvia. It was the weltanschauung of F. Tsander, his sympathy with the revolutionary environment, which allowed him to make the proper decision in 1918 and, doubtless, influenced the bravery and breadth of his "cosmic ideas." In the history of science, as well as the history of art, great creativity is quite frequently born in an atmosphere of revolutionary upthrust, when everything is in motion, everything seems possible. In this case, with the events of October as the background, the possibility of space flight seemed to Tsander, as to Tsiolkovskiy, not so unrealistic at all.

Thus, the entire situation in Riga at the beginning of the century, the environment, the surroundings helped to bring forth in the young Tsander the dream of interplanetary flight and their practical realization -- the construction of rockets. In this respect, the fate of F. A. Tsander was happier than the fate of K. E. Tsiolkovskiy who developed his brilliant, advanced ideas in solitude in provincial Kaluga.

However, it is a long path from the birth of a dream to its practical realization. The question arises: did Tsander work on scientific research while in Riga, are we dealing here with the fantasies of distracted youth or with the true creative work of a young inventor? The answer to this question can be found by studying the archives of Tsander which, fortunately, have been retained.

In the Tsander archives there are many notebooks in which, beginning in 1904, i.e., the 16th year of his age, Tsander recorded "all sorts of experiments, calculations and notes," essentially making these notebooks a daily scientific record. In order to answer the question as to where dreaming stops and independent scientific search begins, we must keep in mind that in the case of born inventors such as Tsander, it is very difficult to draw a clear boundary between the two. We find similar examples in the lives of talented people, of geniuses, for example Blaise Pascal, who found the solution to difficult mathematical problems in his childhood. It would be quite interesting to trace how the thoughts and fantasies of youth gradually give over to engineering calculations, how ideas and discoveries are gradually born. Unfortunately, beginning in 1906-1908, Tsander began recording his thoughts in the unique Gabbel'sberger shorthand system, then widely used in Riga, now almost completely forgotten. The F. A. Tsander collection of the Archives of the Academy of Sciences USSR contains many thousands of pages of these shorthand records of Tsander, the decoding of which has been but recently begun by Yu. V. Klychnikov, concerning whom we shall hear more at these readings. Therefore, we do not yet have a full conception of the early works of Tsander, and can but present a few individual facts [2].

Tsander himself later (in 1924) named 1906 as the year when he began his research on interplanetary flight. In the writings of Tsander not in shorthand, the first report on this subject is dated 10 November 1907. It reads: "Problems of the contruction of a space ship. Conditions determining the shape of the ship. /15
Number of outer walls. Compartments. Device for maintaining the floor in a horizontal position. Can it be done? Like compass on ships. Compressors existing at the present time. Substances absorbing carbon dioxide and other gases which arise. Regeneration of oxygen. Recycling of wastes: garden in spaceship? Room for fuel. Processing of solar heat. Selection of motive power. Construction of buildings for the construction and storage of the spacecraft. Building for supplementary devices and approximate outline of spacecraft" [18]. As we can see, this is an entire program of work. Obviously, Tsander had thought of this problem repeatedly before this date.

In September of 1908, Tsander began a special notebook under the title "Die Weltschiffe (Atherschiffe) die den Verkehr zwischen den Sternen ermoglichen sollen [World Ships (Ether Ships) to Make Voyages Between the Stars Possible. Movement in World Space]". Here, records in clear German alternate with shorthand records.

In 1909, Tsander set forth the interesting idea of the possibility of using parts of the rocket itself as fuel. This idea, as we know, was developed in detail in later works by Tsander, but, as he himself wrote in his monograph of 1932, this idea first

appeared in his manuscript of 11 March 1909. The place was found by Yu. V. Klychnikov in one of Tsander's manuscripts which he decoded ["World Ships..."].

Of course, until the manuscripts of Tsander have been decoded and analyzed by specialists and historians of astronautics, we can give no final evaluation of the early works of Tsander. Obviously, it is difficult to define the boundary between the formation of a problem and the search for its specific and realistic solution. There is still no doubt that his first scientific research in the area of interplanetary voyages and design of rockets was undertaken in 1908-1909. We need but await the successful decoding of his early records and calculations to gain an understanding of the sequence and value of the early conclusions of Tsander. It should be noted that Tsander was quite self-critical of his early works and in some places named 1915 or even 1917 as the date of the beginning of his real work in the area of interplanetary voyages. In this case, apparently, he has in mind not the beginning of this work in general, but rather the beginning of his intensive engineering development of the problem [3, p. 57].

We must study the Riga period in order to create the true scientific biography of F. A. Tsander, which has not yet been written, but which will require the combined efforts of all of our "Tsanderists." When this is done, both underevaluation of the work of Tsander, and unfounded magnification of their value are identically undesirable.

Our other task in the memory of the great inventor is popularization of his work. In Riga, a great deal has been done in this respect. A decision of the Council of Ministers of the Latvian SSR of 1967 created the F. A. Tsander Prize. RPI has created Tsander scholarships; this same Institute has created a small Tsander museum; Bartas Street has been renamed Fridrikh Tsander street; a memorial plaque was installed at the entrance to the home of Tsander in 1962. This building on Fridrikh Tsander Street, a late 19th century house, is located near Zasulauk Station. In this home, Tsander lived for 15 years (1898-1913). The home has been rather well preserved due to the efforts of the family of the teacher E. Schmidt, which has lived in the home for some 40 years. The building is located in a convenient spot. Latvian historians of science have frequently stated (and this has been noted in the resolutions of /16
our Baltic conferences) the need to organize either a memorial F. Tsander museum or, which seems more realistic to us, a museum of the history of technology in the name of F. Tsander with a memorial section dedicated to Fridrikh Arturovich. Latvia is an industrial republic, with significant traditions in the area of technology. To present the work of our scientists and inventors, to show models of technical production such as the first bicycle, the first motor vehicle, the first radio receiver, the first

telephone, the first aircraft motor built in Riga -- this would be a noble and educational project. one has undertaken such a task, and such exhibits are not being collected. Initiative is required, as well as the cooperation of a number of organizations, in order to bring the idea of the creation of a museum of the history of technology to fruition. Of course, this is no simple task, but it is possible, as we hope that sooner or later it will be done. For now, Tsander's home must be taken under the protection of the state, in order to preserve it as a memorial to the history of science and technology.

A memorial to F. Tsander should be created both in his home city and in Moscow. However, the best, the greatest memorial to Tsander is our cosmic science, our successes in the mastery of space. It is not by chance that the second birth of Tsander occurred in 1957-1961 after the launching of the satellites and the flights of the cosmonauts. The connection of these successes with the works of Tsander has been noted by S. P. Korolev, who reported the tremendous influence of Fridrikh Arturovich Tsander, enthusiast of rocket flight, on the workers of GIRD. He combined the gifts of the theoretician and the practical worker. The students of Tsander will never forget his words, "All hail work on interplanetary voyages for the good of all mankind! Ever higher and higher -- to the stars!" [19, p. 159].

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THE BASIC IDEAS OF F. A. TSANDER IN THE AREA OF ROCKET MOTORS

T. M. Mel'kumov

F. A. Tsander was a great and talented engineer, dedicating his entire life to the theoretical and experimental development of the energetic and trajectory problems of interplanetary voyages, beginning these studies independently by his own methods. /17

In the literature we sometimes encounter individual untrue statements concerning F. A. Tsander and his works. Thus, in association with the 80th anniversary of the birth of F. A. Tsander, it was stated that he was a student of K. E. Tsiolkovskiy [1]. This is hardly a criticism of Tsander: to be a student of Tsiolkovskiy is a great honor; however, Tsander never studied under Tsiolkovskiy.

F. A. Tsander studied in Danzig from 1905 through 1907 and began his research in 1907-1908, as a student at Riga Polytechnical Institute. He learned of K. E. Tsiolkovskiy's article "The Investigation of World Space with Reaction Devices," published in Nauchnoye Obozreniye, No. 5, 1903, in the Practical School in late 1904 from his teacher of cosmography.

F. A. Tsander was no more a student of K. E. Tsiolkovskiy than of A. P. Fedorov, R. Goddard, G. Oberth and others. As we can see from the materials in the archives, Tsander acknowledges the priority of Tsiolkovskiy in the statement and development of problems of interplanetary flight, writes of him with deep respect and maintained close and friendly communications with him.

Until not so long ago, some specialists maintained that F. A. Tsander had not studied rocket motors, but rather that his interests were related to air-breathing reaction motors, referring to the OR-1 motor, constructed by Tsander in 1930, which burned gasoline and air. However, the operating principle of the OR-1 motor was that of the rocket motor, though the oxidizer used was compressed air from a cylinder. The OR-2 motor was planned by Tsander to use liquid oxygen and gasoline. Tsander was present at the cold testing of individual units and of the entire OR-2 rocket installation, although the flame testing of the motor was begun 18 March 1933, soon after Tsander went away for treatment [2, pp. 5-8]. Finally, even a passing familiarity with the research and reports of Tsander published during his life and after his death, demonstrates the erroneous nature of the opinion just expressed.

F. A. Tsander was a great and original researcher in the area of rocket technology and the theory of interplanetary voyages. This does not diminish the tremendous achievements of

other great designers and scientists, whose activity in this area began independently and simultaneously with the work of Tsander and yielded results of the greatest significance.

Let us analyze the main ideas which arose in the brain of Tsander or attracted his attention in the area of rocket motors and other power sources for the flight of rockets in interplanetary space. As we do this, we should keep in mind that the development of science and technology after Tsander could not but make corrections to his predictions and suggestions.

F. A. Tsander understood that a rocket motor is not economical at low flight speeds; therefore, in his article "Flights to Other Planets," published in 1924, he writes, "At flight speeds /18
greater than some 400 meters per second, either a rocket adapted for flight in the air or an ordinary purely reaction rocket should be used" [3]. The definitions which Tsander gives in this article, in my opinion, leave no doubt that by a rocket adapted for flight in air he means an air-reaction or combined motor, while by a purely reaction rocket he means a rocket motor as currently defined, not requiring inhalation of air.

In 1926, Tsander, in an incompleted work, presents designs for hydrogen-oxygen rockets using the thermodynamic method considering the dissociation and thermodynamic potentials [4, pp. 64-69].

In two theoretical works under the same title "Thermal Calculation of a Liquid-Fueled Rocket Motor," published posthumously in the collection Raketnaya Tekhnika (No. 1, 1936 and No. 5, 1937), Tsander solves many important problems. He defines the temperature of the combustion products considering the variable heat capacity and dissociation at high temperatures. As the fuel, he analyzes gasoline, as the oxidizer -- liquid air with varying oxygen content: from 23 to 100%.

Tsander studies the process of expansion of the combustion products in the nozzle, determining the velocities and the cross sections along the nozzle. He particularly discusses the determination of the temperature, pressure and velocity in the critical and exit cross sections of the nozzle; he presents approximate calculations of the heat transfer factor and temperature of the walls of the chambers of the rocket motor; he determines the thrust and efficiency of the rocket. In calculating the efficiency, he considers the kinetic energy of the fuel. For that time (prior to 1933), these calculations seem highly qualified and worthy of attention.

In his book "The Problem of Flight with Reaction Apparatus," published in Moscow in 1932, but prepared in 1929-1930, Tsander discusses many problems of interplanetary voyages and rockets and, in particular, properly indicates the increase in efficiency of

rocket motors to 80-90% at altitudes of 45-50 km due to the decrease in atmospheric pressure if the nozzle is designed for these altitudes.

We should note two aspects in the problem of the utilization of the materials of the structure of the rocket as fuel for rocket motors which, according to his own records and information supplied by L. S. Dushkin [2, p. 174], F. A. Tsander began to study in 1909. One, very important aspect, is that the addition of certain metals could significantly increase the specific thrust of a rocket motor. This idea is utilized in modern rocket fuels, for example by the addition of aluminum. This point of view as to the utilization of metallic fuel is quite fruitful. Metals can also be used in special electric rocket impulse or continuous motors, which are now being successfully studied, following the first prototype, investigated by V. P. Glushko in 1929. As concerns the idea of utilization of metal parts of elements of the rocket or aircraft first stage no longer needed as fuel for the rocket, this idea, in our opinion, is unrealistic. If the rocket is carried aloft by an airplane, it would seem more desirable to use this airplane repeatedly for the same purpose than to attempt to burn its parts, which is technically unrealistic. Modern-day development of rocket technology is also following the path of reutilization of the first stages of rockets, which is more economical and fully possible.

F. A. Tsander, utilizing the handbook materials published by Landholt, defines the heat capacities of certain metals (lithium, aluminum, beryllium, magnesium, etc.) and calculates the theoretical exhaust velocities which would be produced, using oxygen as the oxidizer. These theoretical velocities are much higher than those produced by burning gasoline or even hydrogen in oxygen. For example, for hydrogen-oxygen fuel the theoretical velocity under certain calculation conditions reaches 5170 m/sec, whereas for lithium-oxygen and beryllium-oxygen the theoretical velocities are 6330 and 6750 m/sec respectively. /19

Tsander thoroughly understood that it would be impossible to burn only substances yielding solid combustion products. In his article "The Use of Metallic Fuel in Rocket Motors," [2], he writes that the metals would have to be burned together with substances yielding gaseous combustion products, since only in this case could the increase in temperature in the combustion chamber upon combustion of the metals lead to an increase in the total exhaust velocity of the two-phase combustion products. Tsander theoretically and approximately calculated the difference in velocities of gaseous and solid combustion products at the exit cross section of a nozzle and determined the thrust for this case. He produces a formula determining the ratio of thrust force P when the velocity of the solid particles can be ignored, using only their thermal energy to heat the gaseous products, to the

maximum thrust P_{max} which would obtain if the solid and gaseous combustion products had the identical exhaust velocity (P is the ratio of the mass of solid products to the mass of gaseous products of combustion).

Later, Tsander constructs a graph of the function $P/P_{max} = (P, q)$, where q is the ratio of the velocities of solid and gaseous products, q varying from 0 to 200. It is curious that for all values of q from 0.05 up, an increase in the fraction of P over 10 yields a significant increase in the ratio P/P_{max}.

Not limiting himself to theoretical calculations, in the Fall of 1928 Tsander presented experiments on the manufacture of light alloys containing magnesium and other metals, as well as the combustion of strips of magnesium and other alloys with low melting points. Tsander indicated the possibility of atomizing liquid metal with a gas (for example oxygen) and, furthermore, performed experiments on the atomization of a eutectic alloy of 65% Sn + 35% Pb, as well as the alloy 60% Zn + 40% Mg, pure zinc and others with air and oxygen. For a rocket utilizing powdered solid metal fuel, Tsander suggested that liquid oxygen or nitrogen tetroxide be used as the oxidizer.

Let us discuss one more idea which attracted Tsanders attention. Based on the measurements of the force of the pressure of sunlight performed by P. N. Lebedev in 1899 and well known since the end of the 19th century, Tsander, in his article "Flights to Other Planets," in 1924, indicates that flights to other planets in space should best be performed using mirrors made of this sheets. In the prospectus for his book "Flights to Other Planets and the Moon," prepared in 1925 [4, pp. 53-54], he writes of increasing "the effect of the rockets by mirrors, concentrating the light of the sun," and of flights "In Interplanetary Space by Means of Mirrors Alone." In his second article "Flights to Other Planets," first published in 1947 [2, pp. 227-229], Tsander compares rocket flight after the achievement of a velocity of 11.18 km/sec to flight using mirrors and affirms that, by using a mirror with an area of 100,000 square meters and a thickness of 10^{-3} mm, which would weigh about 300 kg (or still less if silver plates were used), a significant savings /20 could be achieved in the weight of the apparatus used for flights, for example, to Mars. He writes that "in interplanetary space, with its tremendous distances and full possibility of using extremely small forces, it is much better to use the pressure supplied for free by the sun..." [2, p. 229]. This plan, currently known as the "solar sail," has been repeatedly discussed and investigated in print and may be realized. As concerns the thickness of the sheets of the mirror, Tsander based his suggestion on the achievements of his time (the thickness of aluminum sheets of 1:2400 mm, nickel sheets 1600 m by 2 m 10^{-3} mm in thickness, etc.) [2, p. 228].

However, though his interest in light pressure for the movement of vehicles in interplanetary space was well-founded, he attached greater significance and attributed greater possibilities to this system than it could really provide. For example, Tsander suggested that sunlight, concentrated by mirrors, might be directed toward another spacecraft, thereby increasing its velocity [2, p. 228]; [3, pp. 15-16]. Of course, this must be attributed to Tsander's then unconscious attraction to the idea of transmission of light energy over great distances for the creation of low-thrust flight vehicles.

Particular attention should be given to Tsander's idea of the utilization of planets along a flight path (their gravitational and electromagnetic fields or their atmospheres) to increase the velocity of flight to the final destination planet. We know from the literature that this idea has been studied in the USA for spacecraft intended for flights to Venus and Mercury [5], then to Jupiter, Saturn, Neptune and Pluto [6, 7].

In addition to the individual unfounded or unrealistic suggestions mentioned above, let us note another, we feel, totally unfounded suggestion for the application of a light electrically charged sphere, which would be repelled from the Earth, since it would have the same charge as the Earth. True, Tsander does caution that this is only possible if the Earth itself has a charge. However, even in this case repulsion from the Earth and flight to interplanetary space of such an apparatus would be impossible, since the force of repulsion of like charges is inversely proportional to the square of the distance between the bodies.

Let us study one important suggestion of Tsander, which, though it does not relate directly to rocket motors, is quite progessive for rocket technology. I speak of the combination of a rocket and an airplane. This combination, in contrast to a pure rocket airplane, to follow the thought of Tsander, consists in that after separation from the Earth and until high speeds are reached (on the order of 400 m/sec), and once more upon return to and during landing on the Earth, an internal combustion engine is used, utilizing the air in its combustion process, while the aircraft also contains a rocket motor, which is put in operation at a speed (over 400 m/sec) and altitude where its process is most effective. As a result, as Tsander writes, "the rocket of my design is embodied in the aeroplane, its reactive force being equal to one-third to one-seventh the weight of the vehicle..." [3]. It is true that it is economically expedient to use large airplanes as the first stage to launch rocket systems into space. We should also recall the space shuttles which have been extensively studied both here and in the USA. Although the structural realization of these two research trends differs from the combined aeroplane and rocket of Tsander, the initial ideas are the same, and if we recall that Tsander wrote these words in 1923-1924, we

cannot but be surprised at his deep penetration into the essence of the systems economically and technically most expedient. We note in passing that Tsander attached great significance to the economic aspects of the solution of this great technical problem. /21

Tsander well understood that piston-type aviation engines could not possibly accelerate an airplane with a rocket to a velocity or lift it to a height where the rocket motor could be economically used. He therefore dedicated a great deal of time to the search for piston machine plans and cycles capable of achieving greater specific power, greater efficiency and lower weight. Apparently, he felt the insufficient efficiency of piston machines, studied other plans of motors utilizing the air and noted the need to investigate air-reaction engines to be installed immovably in an airplane or on the ends of its propellers [2, p. 116].

F. A. Tsander, as was properly noted by M. K. Tikhonravov, "was the first engineer in our country to dedicate himself entirely to the solution of problems of interplanetary flight and activity in the area of rocket technology" [2, p. 3].

An enthusiast and innovator in this area, dedicating all of his efforts, energy and time to the solution of the complex of problems of interplanetary flight, including problems of rocket dynamics and energetics, F. A. Tsander left a shining path through the glorious history of Soviet rocket-space science and technology. His early death prevented the realization of a number of his ideas.

We are fully justified in saying that F. A. Tsander earned the right to be recognized as one of the greatest pioneers in the area of rocket and space science and technology.

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THE IDEAS OF F. A. TSANDER ON INCREASING THE WORKING CYCLE OF A REACTION ENGINE BY MEANS OF AN INVERTED CONE

Yu. A. Pobedonostsev and I. A. Merkulov

In his work [1], F. A. Tsander set forth the idea of increasing the working cycle of a reaction motor by reexpansion of the gas in the nozzle with subsequent cooling and compression of the gas to atmospheric pressure. He set forth and developed this idea in chapters 4 and 6 of his book. In chapter 4, dedicated to jet pumps, F. A. Tsander wrote, "...the gases are heated under a certain pressure, then expand adiabatically...accelerate the motion in the cone, reaching a very low pressure. The gases are then once more compressed, slowing their motion in the opposite cone.... The most important thing here is that a very great quantity of heat should be extracted from the gases during compression" [2]. /22

In the chapter "Reaction Motors with Circular Cycle," the scientist set forth his idea as follows: "...the velocity reached by the gases at the exit from the cone is defined by the expression

$$\frac{W^2}{2g}=\int_{p_z}^{p_a} v dp,$$

where p_z is the pressure of combustion, p_a is the pressure of the free atmosphere at the altitude in question above the surface of the Earth.... If we continue the expansion curve (an adiabatic, polytropic or other curve)...further, then compress the gas along the isotherm...at the lowest possible temperature, the total area, corresponding to the kinetic energy of the gases realized $W^2/2g$ will be...significantly greater...and consequently, the exhaust velocity W, reaction force P and total thermic η_t will all increase" [3].

We should note that the main feature of Tsander's suggestion was the attempt to utilize the thermodynamic cycle of the reaction motor by reexpansion of the gas with subsequent cooling and compression, while the selection of processes by which expansion, cooling and compression of the gas occurred, and the methods of realization of the cycle with reexpansion must be looked upon only as examples, illustrating his main idea. The scientist himself emphasized the generality of the idea he was setting forth. He stated that the compression of the gas on the isotherm did not necessarily have to start at the point of minimum pressure. In the same chapter, he states, "We could in general greatly cool the

gas during reverse compression, or first cool the gas at the lowest pressure, then compress it, while cooling it, to pressure p_a." And further, "We could begin secondary expansion on the curve of compression at a certain special point, using, for example, polytropic expansion with subsequent compression..." [4].

Concerning the methods of cooling of the gas, Tsander wrote, "Cooling might be either by air (with longitudinal ribs) or by water; one could also utilize liquefied gases if available (O_2, H_2, etc.)" [5]. Subsequently in the technical literature a device in which this idea was to be realized came to be called a "Tsander inverse cone." /23

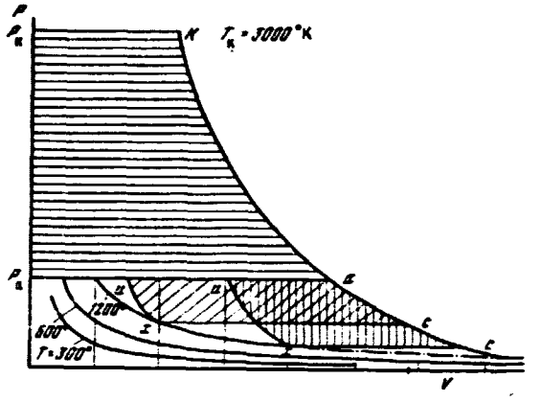


Figure 1

In the present work, we will not analyze the reality or effectiveness of the methods of cooling of a supersonic stream of gas. The purpose of the present article is to clarify what seemed to us to be the most important questions, as to whether reexpansion of gas could be used significantly to increase the area of the ideal thermodynamic cycle of reaction engines, for which types of engines and with which parameters would a significant increase in the area of the cycle be achieved.

Since we are setting ourselves the task of evaluating the idea of F. A. Tsander of the "inverse cone," the study will be performed for an ideal gas, assuming constancy and equality of the polytropic index for all processes.

As an example, let us study the Rankin cycle (Figure 1), in which the increase in area achieved by the idea of Tsander is realized by reexpansion of the gas along the polytrope a-c, cooling along the isobar c-x and compression along the polytrope x-u. Among the parameters defining the relative increase in area of the cycle are the temperature of the gas at the end of the combustion chamber (T_k) and the temperature to which the gas can be cooled in the cooling unit (T_x). Let us introduce a dimensionless parameter -- the temperature ratio T_k/T_x. The numerical values of this parameter may vary. The gas temperature in the combustion chamber can be considered to be T_k = 2000-4000 K, the

temperature of the cooled gas can be accepted as liquid hydrogen temperature ($T_x \approx 30$ K), or the temperature of the atmospheric air ($T_x = 300$ K) or some higher value. Therefore, the parameter T_k/T_x may vary in a general theoretical investigation over broad limits, for example from $T_k/T_x = 2$ to $T_k/T_x = 100$.

The main parameter characterizing the initial cycle of the motor is the ratio of pressures of the gas in the chamber to the pressure of the surrounding atmosphere $\pi_k = p_k/p_a$. For various values of this parameter, the increase in area of the cycle has been defined with variable values of reexpansion of the gas, characterized by the pressure drop in the additional portion of the nozzle $\pi_c = p_a/p_c$. /24

The area of the initial Rankin cycle

$$L_R = \int_{p_k}^{p_a} v\,dp$$

with constant polytropic index n, as we know, is

$$L_R = RT_k\left[1 - \frac{1}{\pi_k^{\frac{n-1}{n}}}\right].$$

The increment in area achieved by the use of the Tsander "inverse cone" can be represented as

$$\Delta L_{ts} = L_{ts} - L_R = \oint_{acxu} v\,dp = RT_a\left[1 - \frac{1}{\pi_c^{\frac{n_1-1}{n_1}}}\right] - RT_k\left[1 - \frac{1}{\pi_c^{\frac{n_2-1}{n_2}}}\right],$$

from which, assuming $n_1 = n_2$, we find the relative increment in cycle area

$$\Delta\bar{L}_{ts} = \frac{\oint_{acxu} v\,dp}{\int_{p_k}^{p_a} v\,dp} = \frac{T_a - T_k}{T_k}\cdot\frac{1 - \frac{1}{\pi_c^{\frac{n-1}{n}}}}{1 - \frac{1}{\pi_k^{\frac{n-1}{n}}}}. \qquad (1)$$

Or, replacing T_a and T_u using the polytropic equations by the values of T_k and T_x:

$$\Delta\bar{L}_{ts} = \frac{1-\frac{T_x}{T_k}\pi_c^{\frac{n-1}{n}}\pi_k^{\frac{n-1}{n}}}{\pi_k^{\frac{n-1}{n}}-1}\frac{\pi_c^{\frac{n-1}{n}}-1}{\pi_c^{\frac{n-1}{n}}}. \tag{1'}$$

The ratio of the area of the Tsander cycle to the area of the Rankin cycle

$$\bar{L} = L_{ts}/L_R = 1+\frac{1-\frac{T_x}{T_k}\pi_k^{\frac{n-1}{n}}\pi_c^{\frac{n-1}{n}}}{\pi_k^{\frac{n-1}{n}}-1}\frac{\pi_c^{\frac{n-1}{n}}-1}{\pi_c^{\frac{n-1}{n}}} \tag{2}$$

and the ratio of exhaust velocities of the gas for both cycles under the assumptions made will be

$$\bar{W}_u = \frac{W_u}{W_a} = \sqrt{1+\frac{1-\frac{T_x}{T_k}\pi_k^{\frac{n-1}{n}}\pi_c^{\frac{n-1}{n}}}{\pi_k^{\frac{n-1}{n}}-1}\frac{\pi_c^{\frac{n-1}{n}}-1}{\pi_c^{\frac{n-1}{n}}}}. \tag{3}$$

On Figure 2 we show the dependence of the increase in exhaust velocity of the gas $\Delta\bar{W} = (W_u - W_a)/W_a$, achieved due to an increase in the area of the cycle. The figure shows curves constructed for various values of the parameter π_c. The calculations were performed for $T_k/T_x = 10$ with a polytropic index n = 1.333.

The picture gives us an idea of how the increase in the area of the Rankin cycle by means of the reexpansion of the gas in the nozzle as suggested by Tsander could be developed in the ideal case. /25

First of all, we see clearly that with large values of π_k, the increase in the area of the cycle in the ideal case yields an insignificant velocity increase. For example, for $\pi_k = 30$ for

all of the values of π_c studied the increase in velocity is less than 10%. Where $\pi_k \geq 80$, as calculations have shown, it is not over 5%. Therefore, the use of the Tsander inverse cone on rocket engines with a pressure drop in the nozzle $\pi_k \geq 100$ is not worthy of analysis even in the theoretical aspect, regardless of the reality or unreality of methods of cooling of a supersonic gas stream. (For motors operating in space or in the thin layers of the atmosphere, the question of the inverse cone, clearly, cannot be analyzed in principle.)

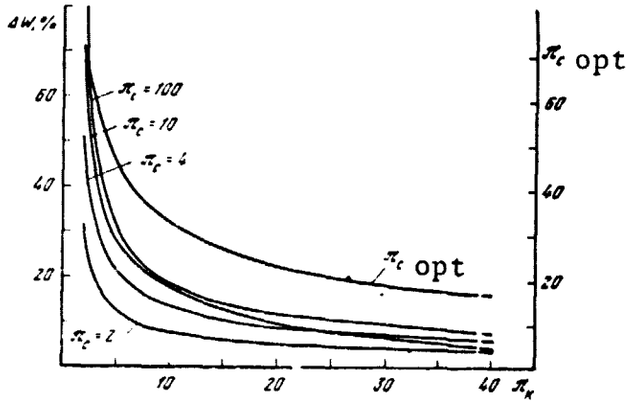


Figure 2

Secondly, we can establish that for Rankin cycles with small pressure drops, i.e., where $\pi_k < 10$, the increase in the area of the cycle if realized would, if the processes were idealized, produce a significant increase in exhaust velocity. For example, where $\pi_k = 10$ it might reach 20%, while where $\pi_k = 4$ -- even 40% or more.

The graph also shows the significance of the degrees of extra expansion of the gas in the inverse cone. As parameter π_c increases, the increase in velocity also significantly increases. Thus, for $\pi_k = 4$, where $\pi_c = 2$ the increase in velocity is 15%, while where $\pi_c = 10$ it reaches 34%. At the same time, as we can see from the graph, an increase in π_c leads to an increase in the area of the cycle only within certain limits, beyond which the increase in π_c not only does not lead to an increase in ΔW, but, quite the contrary, even reduces the increase in velocity in comparison to that achieved with lower values of π_c. For example, where $\pi_k = 4$, an increase in the reexpansion to $\pi_c = 100$ generates an increase in the velocity rise to $\Delta W = 50\%$, where $\pi_k = 9$ the increase in velocity is the same for $\pi_c = 10$ and $\pi_c = 100$, while where $\pi_k = 10$ the increase in velocity where $\pi_c = 100$ is less than where $\pi_c = 10$ (these figures relate to $T_k/T_x = 10$). Figure 1 shows the increase in the area of the cycle for two different values of π_c. As the reexpansion increases, the height of the additional area increases, but for a given cooling temperature T_x,

in the case at hand (polytropic compression), this causes a reduction in the range of change of gas volume upon cooling. Consequently, for each value of π_k with a given cooling temperature T_x there is an optimal value of π_c which realizes the maximum increase in cycle area. In order to determine this value of π_c, we must find the derivative and set it equal to 0: /26

$$\frac{dL}{d\pi_c}=\left[1-\frac{T_x}{T_г}\pi_k^{\frac{n-1}{n}}\pi_c^{\frac{n-1}{n}}\right]\frac{n-1}{n}\pi_c^{\frac{1-2n}{n}}-\frac{n-1}{n}\frac{T_x}{T_г}\pi_k^{\frac{n-1}{n}}\pi_c^{-\frac{1}{n}}\left[1-\pi_c^{\frac{1-n}{n}}\right]=0, \quad (4)$$

from which

$$\pi_c^{2\frac{1-n}{n}}=\frac{T_x}{T_г}\pi_k^{\frac{n-1}{n}},$$

$$\pi_c=\frac{\left(\frac{T_г}{T_x}\right)^{\frac{n}{2(n-1)}}}{\pi_k^{1/2}}. \quad (5)$$

For the value of polytropic index accepted, equation (5) can be written as

$$\pi_c=\frac{(T_г/T_x)^2}{\sqrt{\pi_k}}.$$

Figure 2 shows the optimal value of π_c as a function of π_k for $T_k/T_x = 10$.

In the present work we have analyzed only one particular case of an increase in the area of the thermodynamic cycle based on the ideas of F. A. Tsander. Since we have found an area of the parameters of the cycle in which this increase in cycle area theoretically, for idealized processes, yields a significant result, it seems expedient to continue the theoretical investigations of this idea of Tsander, analyzing the case of large values of parameter T_k/T_x in other combinations of processes occurring in the "Tsander inverse cone" (for example, cooling on an isobar and isothermal compression), and the effect of increasing area as applicable to the Brighton cycle. Along with investigation of the ideal cycle, it would be of interest to investigate the possibilities of realization of the Tsander cycle comprehensively.

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THE STRUCTURAL PECULIARITIES OF THE PLAN FOR THE INTERPLANETARY AEROPLANE-SPACECRAFT OF F. A. TSANDER

Yu. V. Biryukov

> The area of rocket design has been little developed. Further energetic work in this area would be desirable, giving us the possibility of reaching out into interplanetary space, spinning around the Earth...and gaining, flying further, new freedom, new capabilities, new worlds.
>
> F. A. Tsander

The creation by F. A. Tsander in the early 20's of a plan for a spacecraft is a remarkable step in the history of astronautics. This was the first technical plan for a specific flight vehicle intended for flight outside the Earth's atmosphere, a plan which was rather deeply theoretically and structurally developed and, secondly, this plan included a number of original, basically new solutions, bringing the time of practical achievement of space flight significantly closer. /27

Naturally, in any work which analyzes the development of rocket and space technology in the USSR, Tsander's spaceship plan is usually studied However, this analysis has generally consisted only in noting some of the individual advantages of Tsander's plan in comparison to the plans of Tsiolkovskiy and other scientists and inventors and it has been found that these advantages facilitated the solution of the problems of astronautics. Up to the present time, no general historical-technical analysis of this plan, no analysis of its role in the development of rocket and space technology has been conducted, the reasons why this project, having such obvious advantages, was never brought to fruition have never been analyzed.

It is still impossible to give a sufficiently complete analysis, since the major portion of the plan decisions and other materials on the spacecraft aeroplane, recorded by Tsander in his technical stenographic notebook, have not been interpreted, and the final product materials of the plan (drawings, calculations, explanatory notes and model of the spacecraft) have never been found and, possibly, have not been conserved; nevertheless, in this report I shall attempt to approach such an analysis.

In late 1904-early 1905, Tsander became familiar with the classical work of K. E. Tsiolkovskiy "The Investigation of World Space by Reaction Devices" [1, p. 56]. Tsiolkovskiy then solved

the problem of the possibility of space flights in general, from the standpoint of principle, presenting specific technical suggestions for the design of a space rocket only in his supplementary conclusions, demonstrating the reality of the idea, and warning that his work "...falls far short of analyzing all aspects of the problem and of solving it from the practical point of view...." [2, p. 139]. In contrast to him, Tsander made it his life's work to achieve practical solution of the problem of space flight, and all of his further activity, beginning with his engineering education and ending with the investigation of the most widely varied, frequently quite fantastic problems for his time, was subordinated to this goal, which later led to the creation of his plan.

He approached his work on his plan gradually. Thus, in one of his manuscripts of 1907, he records his first thoughts concerning the plan in the form of the statement of the problem for development:

"Problems of construction of spacecraft. Conditions determining shape of spacecraft. Number of outer walls. Compartments...approximate outline of spacecraft" [3].

Further records from the same period show that Tsander at that time either was not able to study the work of Tsiolkovskiy in detail, or at first did not understand even the important problem of liquid fuel as a power source for the motion of a spacecraft. But soon, obviously due to his own investigations, he came to understand this problem and the problem of the importance of the relationship of the mass of the rocket consumed to the mass remaining. He later noted that "in my manuscript of 11 March 1909, I set forth the idea of the desirability of using the entire mass of the rocket as fuel. I always held forth on this point when I argued with my relatives and comrades concerning the possibility of interplanetary voyages" [4, p. 71]. This though led Tsander to the idea of using the metal of the structure of the spacecraft itself as fuel. The idea was finally formulated, apparently before 1917, when he "made a crucible at the plant for experiments on the combustion of melted metal" [4, p. 71]. /28
Studying this idea, Tsander saw that it provided a genuine possibility even at the level of technology then current of solving the problem of achieving escape velocity, and he immediately began to work on the development of the technical plan for the spacecraft, in an area where no one had previously worked.

As he worked on his plan, he asked himself whether the atmosphere itself could be used to make space flight easier, and answered in the affirmative. He suggested that a wing, its lifting force, i.e., the aviation method of flight, be used in the lower layers of the atmosphere, showing that this method has a number of advantages over the rocket-dynamic method first suggested by N. I. Kibal'chich and deeply studied by K. E. Tsiolkovskiy. It is still more important that Tsander suggested that the return from

space be made utilizing only the braking provided by the resistance of the atmosphere. This provided a particularly great gain. It is reasonable to note that Tsiolkovskiy and Condratyuk reached this same conclusion in their own subsequent investigations.

The first version of the plan was completed in 1920 and reported to a Special Commission on Inventions on 10 October 1920 [1, p. 17]. According to the plan, the spacecraft consisted of a carrier, a large biplane with a powerful four-propeller internal combustion engine of a special design allowing it to operate at high altitudes and speeds; a liquid-fueled rocket engine (LRE), designed to use liquid oxygen and liquid fuel plus melted metal fuel, and of the spacecraft itself, a small airplane equipped with devices for interplanetary flight and wings for descent through the atmosphere of the Earth or another planet [5, pp. 24-29].

In the opinion of Tsander, his ship had the following advantages over the rocket suggested by Tsiolkovskiy (whose works at that time analyzed only single-stage rockets).

1. Whereas a rocket, even using the most effective known fuel, hydrogen plus oxygen, could not achieve escape velocity with any realistic ratio of masses, the spaceship-aeroplane, burning both liquid fuel and its own structures to achieve the required thrust, could easily achieve the necessary velocity. Only 1/20th of the launch weight was to be thrust into space, i.e., with a launch weight of 5000 kg the weight of the spacecraft in orbit around the Earth was to be 250 kg, which Tsander originally considered quite sufficient for the flight of one man in space [1, p. 18].

2. Furthermore, Tsander considered that even if a rocket could be constructed with an extremely high ratio of masses, its weight would be greater than the weight of the spaceship-aeroplane by 10-30 times, i.e., would be on the order of 200 tons, a mass which seemed unrealistic at the time, particularly in comparison with 5 or even 10 tons [5, p. 226].

3. The spaceship-aeroplane required much less thrust. The thrust of its rocket motor was to be 1.5 t. The thrust of Tsiolkovskiy's rocket motor, according to Tsander would have to exceed its launch weight by a factor of 4 to 10, i.e., would have to be on the order of 400-1000 t, concerning which Tsander quite properly remarked that his rocket, installed on an airplane, "would be easier to construct as a new design than a self-lifting rocket..." [5, p. 222].

4. Since the absolute dimensions and thrust capacity of the spaceship-aeroplane were significantly less than those of a single-stage rocket, the loads on its structure would also be less and, consequently, it would be easier to build.

5. Since a portion of the fuel was to be carried in the form of structural parts, the ratio between the weight of material receiving the load and the weight of liquid fuel in the spaceship-aeroplane was more favorable for achievement. /29

6. The descent from orbit by means of wings would not require the consumption of fuel, whereas the descent by reducing the velocity by means of firing the rocket motor would require the consumption of the same amount of fuel as insertion into orbit, as a result of which the entire task of human space flight becomes unrealistic [5, p. 20].

7. In the denser layer of the atmosphere, rather low speeds can be used and, therefore, losses to atmospheric drag can be minimized [5, p. 20].

8. The much lower acceleration of the spaceship-aeroplane creates more favorable conditions for the crew and does not require the use of antiacceleration devices such as the liquid-filled baths suggested by Tsiolkovskiy.

9. Due to the possibility of gliding descent in case of a motor failure or during return from space, flight safety is greater and the landing spot can be freely selected.

10. Due to the slower insertion into space, the spaceship-aeroplane could be controlled much more easily and precisely, whereas in the case of a rocket "great errors would be probable due to the rapidity of changes in velocity" [1, p. 48].

11. Flight testing of the spaceship-aeroplane for the aviation portion of its flight would be much easier to perform, since they could be undertaken, like the testing of ordinary aircraft, by gradually increasing the altitude and velocity of the flight, unlike testing of a rocket, which requires quite a different approach [5, p. 23].

12. "...The combination of a rocket with an aeroplane allows the tremendous experimental material accumulated by aviation to be used for interplanetary voyages" [5, p. 222].

The basic proof presented by Tsander for the reality of achievement of orbital velocity by his flight vehicle was as follows: according to his calculations, flight into space would require an apparatus with a launch weight of 5 tons, and there were already airplanes in existence with take-off weights on the order of 50 tons, so that if the mass ratio of 20:1 should prove to be insufficient due to unfavorable test results, a launch weight of his spaceship-aeroplane of 50 tons, with a mass ratio on the order to 200:1, would clearly be sufficient. The breakdown, combustible design of his spaceship-aeroplane allowed in principle an almost unlimited increase in mass ratio [1, p. 21].

All of these advantages were discovered by Tsander due to the fact that he most fully understood the need to use the multistage principle for space flight, which in its most general form consists in that motors and flight vehicles of different types must be used for different stages of the space flight, types most suitable for each particular stage, while a portion of the structure, after it becomes unnecessary for further flight, must be either used as an additional source of matter and energy (in this case the energy is used most effectively) or must be simply discarded (in which case a portion of the energy is lost, but energy is no longer expended to change the velocity of the unneeded ballast).

At almost the same time as Tsander, R. Goddard, G. Oberth and K. E. Tsiolkovskiy came to the principle of multiple stages, /30 but they set forth this principle in its clearest and simplest form. They intended to reach escape velocity by staging and jettisonning similar liquid-fueled rockets of decreasing size, proving the possibility in principle of solving the problem. Tsander in his plan showed not only this possibility, but also showed how the problem could be solved most economically. In his early works he never mentions simple jettisonning of parts of the spacecraft no longer necessary but, obviously, not because he could not see this simple possibility, but rather because this "wastefulness" was quite incompatible with his nature. Even speaking of the need to burn a portion of the structure of the spaceship-aeroplane, he repeatedly returned to demonstrations of the economy of this move [5, pp. 223-224; 1, p. 40], and undertook studies to determine the conditions under which the gain thus realized was retained [6].

The multistage principle allowed Tsander to make another important discovery and a quite different approach to the design of the spacecraft itself. Science fiction authors had frequently utilized light pressure for the voyages of their heros, but in the first book which analyzed the possibility of space flight from the scientific point of view [7], solar sailing was consigned together with the use of centrifugal force and gravitational fields to the ash heap of impossible plans, since the pressure of the sun is quite small. Tsander, however, showed that after a vehicle reached open space, even this negligible pressure, acting over a long period of time, could be successfully used to accelerate a spacecraft from orbital velocity to escape velocity, and even higher velocities, giving a strict theory of the motion of spacecraft under solar sails and several versions of the design of such vehicles. With equal accuracy he showed the possibility and expediency of using "solar electric" motors, centrifugal force, gravitational, electrostatic and electromagnetic fields for acceleration and deceleration of motion in space.

Without discussing all of these developments of Tsander in detail, since they will probably form the subject of future special investigations, we must conclude that the practical goal

of Tsander, which led him to the development of his plan for his spaceship-aeroplane, immediately equipped him with the proper dialectic approach to the problem (the principle is not whether the spaceship should be an airplane or a rocket or a solar sail ship, the principle is that it should be an airplane and a rocket and a solar sail ship). Tsander did not blindly accept the opinions of his predecessors, even the opinion of Tsiolkovskiy whom Tsander read extensively and on whose work he partially based his own. Tsander approached his problems as a discoverer, conducting his developments on the scientific mathematical evaluation of each probable means of putting a spacecraft in motion from the standpoint of its effectiveness and based on the possibility of its achievement; therefore he frequently came to results which differed significantly from the results of scientists who studied the problem purely theoretically.

But let us return to the design of the interplanetary spaceship-aeroplane. Tsander developed this design to the level of a draft plan, developing the individual units and systems still more deeply. In 1925 he wrote that in addition to the 650 pages written in shorthand, various scientific and technical calculations in this area "...there are 27 drawings averaging 50 x 70 cm in size, on which I have drawn the structures necessary for experiments, parts of the motor and the aeroplane-interplanetary spaceship" [1, p. 58]. /31

In developing the design of his spaceship, he made significant use of the achievements of airplane building of the time. Even for the most original design peculiarity of his apparatus he sought technical prototypes in existing designs of retractable landing gear and wings with area capable of variation in flight, which had just appeared at that time [1, p. 21]. In general, the problems of folding and combustion of the structures of a large aeroplane, including the lifting and rudder surfaces, propellers, motor, fuselage, empty fuel tanks were given particularly great attention by Tsander, who developed the plan to the extent that "...the weight of the aeroplane will be but slightly greater than the weight of an ordinary aeroplane." [5, p. 21]. A special system consisting of cables and winches was developed to pull in the portions no longer in use, controlled "...by switching on and off of supplementary motors, simply designed and themselves capable of later serving as fuel" [5, p. 226]. The primary structural materials were aluminum and magnesium alloys, which are effective fuels. The parts of refractory materials necessary for the engines and other units would remain in the boiler, held up by a special screen. After the liquid metal was melted, it was to be fed by an injectoror centrifugal pump to the LRE combustion chamber and there burn together with the gasoline or hydrogen and oxygen.

The small aeroplane, or the spaceship itself, was mounted in the large aeroplane not as a unit whole, but rather in parts, so that the lifting force of its surface and the thrust of its

engine could be used from the very beginning, i.e., so that it was not simply ballast. Subsequently, it was to be assembled for use as the parts of the large aeroplane were consumed [1, p. 18]. By the end of the flight, only the small aeroplane and the only portion of the large aeroplane not used as fuel -- the metal melting boiler -- would be inserted in orbit [1, p. 12].

After his first analysis of the project, Tsander continued to improve it in order to decrease the relative weight of the individual elements and simplify the stowage system. In particular, some of the multiple-cable portions of the retracting system were replaced by single-cable systems.

One very important aspect was the transition from an aeroplane in which the fuel was contained in a sphere to an aeroplane in which the single large containers were replaced by many small containers. This greatly simplified the process of breakdown and combustion of fuel tanks. Tsander came upon the idea of decreasing the volume of special containers as much as possible and placing a portion of the liquid fuel and liquid oxygen in the hollow beams of the structure of the aircraft itself. He therefore not only gained weight, which would have been required for tanks, but greatly lightened the weight of the load-bearing beam itself. He considered that, first of all, since the liquid gases in the rods would be under pressure, this pressure would unload the rod from compressive forces, making the entire structure operate only in extension, i.e., would create the optimal case of loading and, secondly, due to the great reduction in temperature of the rod, would increase the mechanical properties of the materials by an average of 1.5 times [1, p. 19]. Tsander expressed the hope that with such a design, great altitudes and speeds could be achieved even without burning metal parts (1, p. 20]. Tsander understood that a combustible structure was a forced version of his plan, used simply because he saw no other /32
means of achieving escape velocity. He understood that from the standpoint of simplicity of design, "particularly for test flights," and from the standpoint of the highest efficiency of the rocket engine "due to the great quantity of volatile products of combustion in relationship to solid products," it would be best to avoid "breaking down the aeroplane itself," expending only liquid fuel.

Of course, the plan of Tsander had not only advantages, but certain weak points as well (complexity of structures, the need to solve the quite new problem of melting, feeding and burning the metal fuel). The level of technology of the time explains the selection as the first stage motor of a motor-propeller group, simply because at low velocities, a propeller motor has much higher efficiency than a reaction motor. This is also the reason for the contradiction that an internal combustion engine, capable of operating with the oxygen of the atmosphere, was designed by Tsander to increase its altitude capability by burning liquid

oxygen stored on board the ship. True, Tsander felt this shortcoming of his plan and even in the first version spoke of the desirability of replacing the motor and propeller group with "...a rocket, adapted for movement in the atmosphere..." by which he meant a combination system consisting of an LRE and a system of cones for ejecting air in order to increase the flying efficiency at low velocities [1, p. 19]. However, due to the lack of study of this problem, he still selected as his primary version the motor and propeller group, thinking that the motor and propeller group could operate at high velocities as well. Tsander essentially did not have a sufficient conception of the aerodynamics of high velocities, of the sound and heat barriers. The only limitation on the efficiency of his motor and propeller group he saw was the danger of bursting of the propellers due to centrifugal force at extremely high speeds. Due to this, he supposed that the propeller would be useful only up to a speed on the order to 400 m/sec and an altitude on the order of 28 km, i.e., he approached the problem purely mechanically and in this respect the approach of Tsiolkovskiy, who analyzed the physical aspect of the phenomenon, was much deeper.

Of course, Tsander extracted himself rapidly from many such dead ends due to his investigations and due to the fact that he carefully followed all achievements of aviation science and technology. The clearest example of this is the fact that by 1924 he independently came to the idea of using a rocket "drawing in air for combustion," i.e., to the idea of using the oxygen in the air in a jet engine [1, p. 19]. Tsander expected that the gain due to the use of a jet engine could be used by burning only a small quantity of the metal, the remaining portions of the aircraft being held in reserve for unforseen emergencies [5, p. 230]. The idea of using a jet to accelerate the spacecraft in the dense layers of the atmosphere, in addition to the idea of using portions of the structure as fuel, remained dominant in the creative life of Tsander and were used by him not only in the development of his plan for the spaceship-aeroplane, but in his other plans, particularly the plan for a central rocket, surrounded by a number of side rockets and vessels for fuel and oxygen, in a plan allowing, according to Tsander's calculations, a ratio of fuel mass to payload of the spacecraft of something like 1000:1 to be achieved [4, pp. 50, 57].

Gradually as his own new studies and the investigations of other scientists in the area of rocket and space technology progressed, Tsander became convinced of the excessive optimism of his initial idea that a spacecraft could be created quite rapidly, and he became ever more conscious of the gradiose range of problems obstructing the path to the realization of space flight. It became ever clearer to him that the parameters which he used in his own plan were far from realistic. Thus, in the /33

plan of 1924 Tsander increased the weight of his own spacecraft designed for one man by a factor of 2, i.e., to 500 kg [5, p. 32].

One factor which helped Tsander to recognize the true difficulty of the problem was his work on a model spaceship-aeroplane, to which he dedicated much of his attention. He began working on the model apparently in 1922. The main purpose of the model he considered to be the development of the folding and breakdown of its structures for use in the boiler and flight testing. His technical diary includes detailed entries concerning the development of the elements of the model. For example, "An achievement: the four joints which I manufactured came apart easily, after which I ground them down and lubricated them well. I then attached the cables of the first section, checking by fastening them that they all fit through the four joints "[8, sheet 2]. It is interesting to note that here Tsander reports the conditions of similarity which the model must follow in order that the results of its testing might be used for the design of the spaceship-aeroplane. Of these conditions, in particular, he mentions the speed of light of the model, its dimensions, the cross sections of its individual load-bearing elements, the power of the motor, diameter of the propellers, their rotating speed, etc. [8, sheet 109]. However, the work on the model was very difficult, and in 1925 Tsander writes that his model of his interplanetary spacecraft is only half ready [1, p. 58]. At this time, Tsander had realized clearly that among all the other problems, that of creating the rocket motor was a significant one. Although Tsiolkovskiy published the idea of creation of LRE as early as 1903, no information on the practical creation of LRE had appeared in the intervening 20 years. Nothing was known of the conduct of work on the creation of jet engines, either. Therefore, Tsander turned increasing attention beginning at this time to the investigation of engines, and ever decreasing attention to flight vehicles as a whole. When he succeeded in developing his practical work on rocket engineering, it was dedicated 90% to work on engines.

It is also important to note that Tsander gradually changed his opinion concerning the absolute superiority of winged rocket ships over wingless ships. In his presentations, he began to note that there are areas in which ballistic or, as he called them, "lifting" rockets might have advantages over spaceship-aeroplanes, for example the area of unmanned flights into the upper layers of the atmosphere for research purposes. He himself made a number of drawings of designs for wingless rockets: a plan for a competition held by the Society for the Study of Interplanetary Voyages (SSIV) in 1924 [1, pp. 22, 25], drawings of the OR-3 rocket in 1930 [9] and, finally, the first stages of development of the GIRD-X rocket, constructed after his death by the first GIRD team. Apparently, even at this time Tsander could see the trends indicating that reaction technology would be divided in the future into two branches. The first branch, based on the use of the oxygen of the air, became entirely a part of

aviation, supporting its further development, while the second was split off into the independent branch of rocket science, later rocket-space technology. The development of rocket technology was defined not by winged, but rather by ballistic rockets, which allowed man to reach space. Obviously, this occurred because the problems of creation of these rockets, in all their complexity, were still simpler than the problems involved in creation of winged rocket boosters. Also, ballistic rockets were found to be a more serious weapon than winged rockets. Thus, it seems, Tsander's ideas concerning the advantages of winged rockets were inconsistent. To the present day, /34
Tsander's idea of the combustion of metal structures of the rocket vehicle has also never been realized. In his own day, Tsander wrote that "...the only obstacle to the use of the solid combustion products is the possibility of contamination of the rocket with metal oxide" [3, p. 224], i.e., he realized the danger that the solid products of combustion would precipitate on the walls of the chamber of the rocket engine and prevent its normal operation. However, the difficulty in the use of metal fuel proved to be otherwise: no method was ever found to feed the metallic fuel into the combustion chamber of the LRE, in spite of the extensive experimental program undertaken by Tsander himself and by the first GIRD team. This idea was finally abandoned, not only due to the difficulty of performing it, but also due to its nonpressing nature at the time: the use of metal fuels was not only unnecessary for the development of rocket flight vehicles at the time, but in fact provided no essential gain at all. It is therefore obvious that the development of this idea was doomed, even if Tsander had continued to participate in the development of rocket engineering after 1933. Up to this very day, air-aspirating reaction engines have not been used to accelerate space vehicles.

We can therefore ask: what historic significance has this plan if its main ideas have never been recognized or achieved?

It is interesting in this respect to present an evaluation of such plans, written by K. P. Feoktistov. He writes that these plans "...were more a game than science. If a man begins to become interested in some problem, this means that the problem has matured for thought. Any problem stimulates a desire to solve it. Thinking over the solution to the problem leads to the plans necessary for its realization. This is like a chain reaction...the possibility arises of imagining the form of some distant future expedition. And now, the very understanding of this possibility involuntarily accelerates thinking and leads it to new solutions.

"From a simple intellectual game, a specific plan of research, experimental and design work may develop.

"These 'games' become an obligatory stage in the preparatory work, which may last for long years.

"The basis of all of this is that well-understood and natural human weakness -- the impossibility of resisting the temptation, at least mentally, to move ahead of one's own time" [10, p. 29].

The plan for the interplanetary spaceship-aeroplane of Fridrikh Arturovich Tsander played its great historic role primarily because it drew the attention of Soviet society in the 1920's to the problem of astronautics not as an affair of the distant future, but as a problem for the day, and served as a scientific and technical basis for the organization of the world's first society for astronautics -- the Society for the Study of Interplanetary Voyages. His faith in the immediate possibility of his plan helped Tsander to convince many others of this possibility. His plan helped to popularize the idea of astronautics. The fact that the plan was set forth by a graduate engineer, who backed up his conclusions with drawings and calculations, had more influence on the intelligentsia of the time than the work of the provincial teacher Tsiolkovskiy or the unknown inventor Kondratyuk.

Another very important fact for history is the fact that the work of Tsander on his plan for his spaceship-aeroplane was possible primarily due to the direct not only spiritual, but also material support of the working class. The people, after completing a revolution such as none ever seen before in human history, did not look upon this plan as a wild or thoughtless work on an impossible dream of flight to other worlds. On the contrary, this was just the sort of plan which could capture the spirit of the time. /35

Working on his plan, Tsander explained that the primary problems of astronautics were concentrated not in the rubber industry, where he was first sent to work, and not even in the creation of cosmic greenhouses, to which he turned a great deal of attention, but rather in the technology of rocket building. As a result of Tsander's work on his plan, he was able to write, "...since March of 1922, I have been involved exclusively in work on the further development of aviation in my desired direction" [1, p. 17]. As a result of this work, Tsander concentrated his main efforts on investigation of the problems of creation of reaction engines, thanks to which the confused ideas in favor of motors of one type or another were replaced by a clear understanding of the peculiarities and area of application of the jet engine, hydrogen-oxygen LRE and LRE using metallic fuels, new basic plans for engines were set forth, new design decisions were suggested and, finally, practical work was performed, as a result of which the first domestic LRE prototype, the OR-1 was created and the first Soviet LRE which actually flew in rockets, the type 10 and 02 engines were developed. The idea of installing a small LRE on a glider or airplane, based on which GIRD developed the RP-1 rocket plane was also to a significant extent a result of the work on the plan for the spaceship-aeroplane.

However, the ideas which Tsander used in his plan are only of historic significance. As of now, we have completed the first lap in the development spiral of rocket-space technology. And today, thanks to the rapid development of astronautics, thanks to the fact that progress requires continuing expansion of space research and ever greater utilization of the resources of space for national economic goals, the problem of the most economic achievement of space flights is becoming critical. Throughout the world, intensive work is going forward on the utilization of the atmosphere for the acceleration of spacecraft, on the creation of winged rocket boosters and combined air- and spacecraft with combined power plants. Thus, this idea of Tsander has been given second life and is today near fulfillment [11].

Tsander's suggestion for the utilization of parts of the structure as fuel has also not lost its promise. True, it could hardly be used in chemical engines, although new designs embodying his suggestion are constantly set forth and patented, but it is possible that it may be used in engines of a new type utilizing electronuclear energy, where the relative value of each kilogram of mass of the rocket apparatus is much higher and where the costs involved in complicating the plan of the apparatus, when the solid fuel need not be supplemented by liquid fuel and oxidizer, may be easily justified.

Thus, the plan for an interplanetary spaceship-aeroplane developed by Tsander indicates, on the one hand, his surprising technical bravery, even daring, based on a clear understanding of the tremendous importance of astronautics for the progress of mankind and, on the other hand, shows the scientific and technical foresight of this outstanding Soviet scientist and engineer, capable of looking into the future, even beyond our own days.

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THE IDEAS OF F. A. TSANDER FOR THE USE OF AERODYNAMIC FORCES IN THE FLIGHT OF ROCKETS IN THE ATMOSPHERE

I. A. Merkulov

The founder of astronautics, K. E. Tsiolkovskiy, performed many investigations and published a large number of works on aerodynamics, aviation and air travel [1]. In developing the principles of astronautics, Tsiolkovskiy used in this new science many of his ideas from the area of aviation and air travel. In 1911, he set forth the idea of lifting rockets upward using an airship [2, p. 128].

F. A. Tsander has made exceptionally great contributions to the statement and development of the problem of the use of the aerodynamic lifting force during the movement of rockets in the atmosphere. He presented many lectures and reports to popularize the idea of the winged interplanetary spacecraft. Thus, as early as 1921 he read a report on a plan for his own craft at the First Moscow Province Conference of Inventors and Rationalizers. In January of 1924, he presented a report to a session of the Theoretical Section of the Moscow Society of Amateur Astronomers. Tsander demonstrated a model of his winged spaceship at the First World Exhibition of Models of Interplanetary Vehicles and Mechanisms in Moscow in 1927. The reports of Tsander, together with his published articles, were very important in the popularization of the scientific problems of astronautics in general and particularly the idea of the creation of winged rockets.

It has been repeatedly pointed out in the scientific and popular scientific literature that Tsander is the inventor of the winged interplanetary spacecraft. However, it seems to us insufficient merely to state this fact. Tsander produced not one, but many inventions in the area of winged rocket-space systems. He made highly valuable suggestions and set forth many interesting thoughts in the area of winged rockets. It seems therefore desirable to attempt more completely to establish priority of Tsander in the statement and development of the problem of utilization of winged apparatus in rocket-space technology. /37

In his report on the works of F. A. Tsander sent to the Scientific Department of Glavnauka[1] in February of 1927, Professor V. P. Vetchinkin wrote, "...that F. A. Tsander has made a significant new contribution to this difficult problem, including his suggestion to equip a rocket with wings for flight in the atmosphere and for gliding descent..." [4, p. 40].

Tsander himself in his autobiography, writing on 12 March 1927, reports: "As far as I know, I have priority as concerns the following suggestions..." -- and among the first he lists the

[1]Main Administration for Science

suggestion "to equip the rocket with wings for flight in the atmosphere and to produce a velocity of approximately 8 km/sec in the upper layers of the atmopshere, and also for gliding descent from interplanetary space to the Earth or to other planets which have atmospheres..." [3, p. 22].

On 20 January 1924, Tsander spoke at the Theoretical Section of the Moscow Society of Amateur Astronomers, reporting on the design of his interplanetary spacecraft and flights to other planets. In the "abstract of the report of F. A. Tsander," it is stated: "...he suggested a new method for flight to other planets: a combination of an aeroplane with a rocket.... He showed and explained a drawing of such an interplanetary ship and indicated the advantages to be achieved by the use of his suggested method of flight in comparison to lifting rockets..." [3, p. 27].

In the first printed work of Tsander, dedicated to interplanetary voyages, published in 1924 in the journal Tekhnika i Zhizn', No. 13, under the title "Flights to Other Planets," he states: "I have developed the following main positions. 1. For flight in the higher layers of the atmosphere...it would be desirable to use an aeroplane as the structure supporting the interplanetary spaceship in the atmosphere" [5, p. 259]. And subsequently in the same article, he states, "The tremendous dimensions of the booster rocket can be greatly reduced. K. E. Tsiolkovskiy suggested that a rocket be used for interplanetary voyages, but not in combination with an aeroplane. According to him, the reaction force of the rocket in flight must support the weight of the entire interplanetary spacecraft and accelerate it. These rockets are called boosters or lifting rockets. The rocket of my design is hidden within an aeroplane, requiring a reaction force of but 1/3 to 1/7 of the weight of the spaceship. It would be much easier to construct such a rocket, rather than the huge rocket of Tsiolkovskiy" [5, p. 261].

In the text published in the journal, it was written, "K. E. Tsiolkovskiy suggested that a rocket be used in combination with an aeroplane for interplanetary voyages" [6, p. 16]. Tsander, in the copy of the journal which he received, inserted after the word "rocket" the words "but not yet" and made the notation, "in printing the abbreviated version of the article, the words 'but not yet' were omitted by mistake. I have reported this error to the editors" [7].

The suggestion that Tsander when he wrote the article (it was completed in 1923) had noted the idea of Tsiolkovskiy, but then, by the time he received his copy of the journal, had forgotten this or that the correction was made by the editors of the journal, who were familiar with the works of Tsiolkovskiy, must be rejected as inconsistent. All of the subsequent text of the paragraph extracted above compares the rocket of Tsander to the rocket of Tsiolkovskiy and makes sense only with Tsander's correction of the first sentence. /38

A patent application of Tsander, filed with the Committee for Inventions on 8 June 1924, is of great interest and particular documentary value. It states:

"Up to now, suggested designs of interplanetary vehicles have had the following primary shortcomings, avoided in my design.

"1. The need for tremendous expenditure of fuel during the return to Earth by firing the rocket...

"2. Dynamic support of the rocket by the gases streaming from the rocket.

"3. The need to use tremendous accelerations...

"4. The tremendous size of the rocket for a given weight of interplanetary spacecraft...

"In the design which I suggest here, the rocket is combined with a dismountable aeroplane, driven at low altitudes by an engine of a special design, and a much smaller second aeroplane, built one within the other...

"The primary advantage of the design suggested over designs suggested to date is embodied in the following technical and economic facts.

"1. The use of a small aeroplane with wings allows descent by gliding flight to the Earth and to other planets with atmospheres in general. This decreases the total weight of the interplanetary spacecraft which must be lifted from the Earth by a factor of 15 to 20, if the weight of the spacecraft after return to Earth is considered identical in both cases.

"2. The use of an aeroplane for the ascent and descent (for planets having an atmosphere) guarantees the safety of the passengers to a greater extent than the use of parachutes and lifting rockets.... My plan replaces the support of the interplanetary spacecraft by the weight of the rocket with its support by the wings of the aeroplane, so that the interplanetary spacecraft at all times rests safely on its aeroplane, which feature is not to be found in a lifting rocket...

"4. The necessary thrust of the rocket in my design is only 1/6-1/3 of the initial weight of the ship, whereas the necessary thrust with lifting rockets is 4 to 10 times the initial weight of the ship...

"5. Maintenance of my rocket, which is 10 to 60 times smaller than a corresponding lifting rocket, is easier than maintenance of a tremendous rocket...

"6. It is extremely easy to perform experiments with the design here suggested due to the possibility of starting or stopping the motor or the rocket at any minute" [5, pp. 271-275].

These extracts from the works of Tsander show first of all that the scientist conducted orderly and deep development of the problem of utilization of the aerodynamic lift in accelerating the rocket in the atmosphere. This work by Tsander is his creative contribution to the development of this problem and is worthy of the highest evaluation.

Another important service of Tsander is that he attempted to embody all the achievements of aviation in the service of the nascent science of astronautics. He understood that the use of the experience accumulated by aviation would help to accelerate the achievement of interplanetary flight. He spoke and wrote of this many times. For example, in the patent application mentioned above, he stated, "The highly developed technology of aviation and the scientific development of airplane structures in general reduced the dangers which may be encountered in /39
flight more than is possible with a lifting rocket, and thus facilitate the most rapid fulfillment of the plan" [5, p. 275].

It is also to Tsander's great credit that he developed the idea of intercontinental flight on rocket apparatus, the idea of creation of apparatus which have come to be called space airplanes or space shuttles. These ideas were set forth by him in 1924 in the same patent application: "The designs suggested could be used, in addition to interplanetary voyages, also for rapid flights on the Earth in the upper layers of the atmosphere and above it; they could carry cargo and passengers both from one point on the Earth to another, and to interplanetary stations and back from them to a celestial body" [5, p. 275].

Thus, analysis of the works of F. A. Tsander indicates that he was the inventor of the idea of the use of winged vehicles for insertion of spacecraft into orbit around the Earth and has priority in setting forth and developing a number of interesting suggestions concerning the general problem of winged rocket-space systems. Among the suggestions set forth and developed by Tsander in this area we can include the following:

1. The creation of air-space vehicles and their use for intercontinental flights.

2. The creation of a winged space vehicle with variable wing area.

3. The use of wings which retract into the fuselage of a vehicle as fuel.

4. The creation of a single design of a winged space vehicle with a combined power plant, consisting of a piston

engine with a propeller and a liquid-fuel rocket engine (in contrast to the creation of two independent vehicles, each of which has its own power plant).

5. The use of the scientific and technical experience of aviation in the development and creation of rocket-space systems.

6. The use of wings for gliding descent of the spacecraft to planets with atmospheres.

Furthermore, for the first time in history, Tsander developed a plan for a two-stage winged spacecraft. This plan used the suggestions of Tsander outlined above.

We must note that after the launching of the first Earth satellites and particularly after the flights of the Vostok spacecraft, inserted into orbit using a "Tsiolkovskiy lifting rocket," the predictions of Tsander that it would be easier to use winged interplanetary spaceships to fly in space than "lifting rockets" require commentary. The development of rocket-space technology has shown the correctness of the foresight of Tsiolkovskiy, his idea of the possibility of using both methods for insertion of spacecraft into orbit were more correct than Tsander's statement of the clear advantages of winged rockets. However, the question of evaluating the views and suggestions of the two scientists as concerns the use of winged rocket-space systems, in our opinion, is worthy of special investigation. Here, in accordance with our task as previously stated, we have discussed only questions of the priority credit in this area.

Beginning in 1924, the idea of using wings for the flight of rockets in the atmosphere was developed in detail in many aspects and published in the works of Tsiolkovskiy and Tsander. /40
We can assume that during this period these two scientists influenced each other in a fruitful way.

An evaluation of the credits due F. A. Tsander in the development of the problem of winged rocket-space vehicles would be complete if we included only his theoretical works. It is also very significant that Tsander, among the first in world technology, began experimental-design work in the area of winged rocket apparatus. However, we should note that the scientist himself undertook only the first stage of development, i.e., the stage called experimental design work. The scientific ideas of F. A. Tsander and his initiative, supported by the Bureau for Air Technology of the Central Council of Osoaviakhim USSR, played a great role in the organization in Moscow of experimental and research-development work on rocket technology, in the creation of GIRD [8]. F. A. Tsander, together with S. P. Korolev, M. K. Tikhonravov, Yu. A.

Pobedonostsev and other enthusiasts organized and led GIRD. And immediately after the organization of GIRD, F. A. Tsander began to develop the plan for the OR-2 rocket engine, designed to be used on a rocket plane [9, p. 62], while one of the four GIRD teams worked on the development of winged rocket vehicles.

In recent years, the world press has seen the appearance of many books and articles dedicated to the problem of air-space craft, i.e., winged rocket vehicles, using the lifting force of wings while flying in the atmosphere, then moving out into airless space, moving at cosmic speed as artificial Earth satellites. Air-space craft are a new step in the development of rocket-space technology. The abundance of scientific work dedicated to the results of the investigation and plan developments indicate that the ideas of Tsander on the effectiveness of winged rocket apparatus have now become generally recognized. The time is approaching when such apparatus will be put in service in flights in space.

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THE PROBLEMS OF ROCKET DYNAMICS IN THE CREATIVITY OF F. A. TSANDER

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The scientific and technical heritage of F. A. Tsander is extremely varied and has many levels. Its development is being conducted in various directions, encompassing a significant fraction of the problems which compose the foundation of modern rocket-space science and technology. However, we must note that the developing traditional idea of Tsander as an enthusiast of interplanetary flights sometimes unjustifiably distracts the attention of scientific research historians to those aspects of his activity which were primarily defined by purely "space" problems. /41

In particular, this tendency has been noted in the investigation of the creativity of Tsander in the area of the flight dynamics of flight vehicles, within the framework of which up to the present time we have essentially seen only the developments of Tsander concerning the theory of space flight (astrodynamics).

The present work is an attempt to fill this gap in the development of the scientific and technical heritage of Tsander, by discussing the complex of problems relating to the investigations of Tsander on rocket dynamics. The most important of these problems are the following.

1. A general "technical" commentary of the significant aspects of the creativity of Tsander concerning the dynamics of the flight of ballistic rockets.

2. A comparative description of works in which problems similar to or to a great extent accompanying problems touched in these developments of Tsander were solved.

3. A comparative analysis of the results of the works of Tsander with the development of the corresponding problems in modern rocket dynamics.

1. In the present work we analyze the developments of Tsander concerning the flight dynamics of rockets, the basic tactical characteristics of which correspond to the current-day class of machines called long-range ballistic missiles (LRBM).

These developments include materials published in the 15th section of Tsander's book Problema Poleta pri Pomoshchi Reaktivnykh Apparatov [The Problem of Flight by Means of Reaction Apparatus] [1, pp. 55-76]. In this section, the content of which generally defined the range of investigations of Tsander in the area of

rocket dynamics, he analyzed the following problems:

-- the development of a rocket system, determination of the parameters of motion and elements of the trajectory of the flight of the LRBM;

-- optimization of LRBM flight based on the conditions of minimum velocity at the end of the powered flight sector;

-- investigation of the possibility of "superlong range" flight from the standpoint of providing the necessary fuel reserve on board the rocket.

The possibility of analytic investigation of the first two problems was determined by the nature and volume of the necessary assumptions, allowing Tsander to reduce the solution of the problem of the motion of a rocket during the passive sector of the trajectory to the solution of the problem of free motion of a material point in a central force field.

With these assumptions, using the laws of Kepler and the properties of elliptical curves, Tsander produced a system of equations, with which he defined the basic elements of the trajectory and the initial free flight velocity (V): /42

$$e = r_2 - a, \tag{1}$$

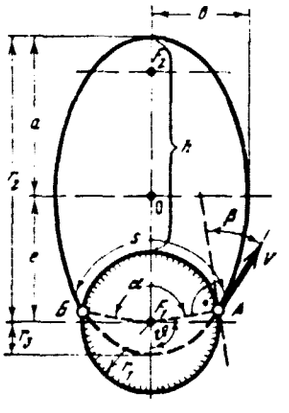
$$\Sigma = (r_2 - a)/a, \tag{2}$$

$$b = \sqrt{r_2(2a - r_2)}, \tag{3}$$

$$\cos\vartheta = \frac{a(2r_2 - r_1) - r_2^2}{r_1(r_2 - a)}, \tag{4}$$

$$V = V_3\sqrt{2 - r_1/a}, \tag{5}$$

where e and Σ are the eccentricities of the ellipse (absolute and relative); θ is the true anomaly of the initial point of departure; V_3 is the circular velocity necessary for flight in a circle of radius r_1; r_1 is the radius-vector of the ellipse at the initial and final points of the flight (taken in Tsander's calculations equal to the radius of the Earth); a and b are the semimajor and semiminor axes of the ellipse.



Equations (1)-(5) together with the expression for flight range S, established from simple geometric relationships (figure)

$$\alpha = 360^\circ - 2\vartheta, \tag{6}$$

$$S = r_1\alpha\frac{\pi}{180^\circ} = \frac{\pi r_1}{90^\circ}(180^\circ - \vartheta), \tag{7}$$

allow us to calculate the elements of the elliptical trajectory and the main kinematic parameters of the flight V, β. Here α is the central angle, corresponding to the flight range measured at distance r_1 from the center of the Earth; β is the angle of elevation of the rocket at the initial point of free flight.

After indicating that equation system (1)-(5), which contains 7 unknowns, is solved in the general case with any two variables known, Tsander states a new problem -- the extremal problem of determination of the conditions under which a fixed flight range can be achieved with the minimum initial velocity [2, p. 464]. The study of this problem leads Tsander to the conclusion that the statement of the problem of the search for conditions under which an assigned range can be reached with minimum flight velocity is correct only if the flight range does not exceed half the circumference of the Earth (20,000 km). For the case of flight over a range not exceeding 20,000 km, Tsander produced the necessary relationships allowing the main kinematic parameters of motion of the rocket to be determined for the optimal trajectories:

$$V_{\min} = V_3 \sqrt{\frac{2 \sin \vartheta}{1 + \sin \vartheta}}, \tag{8}$$

$$\beta_{opt} = \frac{\vartheta}{2} - 45°, \tag{9}$$

and considering (7)

$$\beta_{opt} = 45° - \alpha/4. \tag{10}$$

Attempting to develop calculation plans allowing determination of the desired parameters with any combination of initial data, Tsander composes various systems of equations reflecting the specific form of these initial conditions. In particular, he composed an equation system by which he sought out the flight parameters as a function of and subsequently converted these equations by means of expression (9) to equations in which the only argument is β_{opt}. Our attention is drawn by the simplicity of the calculation dependences which Tsander composed for determination of the parameters of the trajectory and motion as a function of β_{opt}[1]: /43

[1] We will in the future speak exclusively of the optimal trajectories -- the trajectories of minimal energy (TME), for brevity we will replace the symbol β_{opt} by $\tilde{\beta}$. The parameter $\tilde{\beta}$ will be taken to mean its optimal value.

$$\tilde{\beta} = 45^\circ - \frac{45S}{\pi r_1}, \tag{11}$$

$$V = V_a \sqrt{\frac{\cos 2\tilde{\beta}}{\cos^2 \tilde{\beta}}}, \tag{12}$$

$$\alpha = 180^\circ - 4\tilde{\beta}, \tag{13}$$

$$a = r_1 \cos^2 \tilde{\beta}, \tag{14}$$

$$b = r_1 \cos \tilde{\beta} \sqrt{\cos 2\tilde{\beta}}, \tag{15}$$

$$\Sigma = \operatorname{tg} \tilde{\beta}, \tag{16}$$

$$r_2 = r_1 \sqrt{2} \cos (45^\circ - \tilde{\beta}) \cos \tilde{\beta}, \tag{17}$$

$$h = r_1 \sqrt{2} \sin (45^\circ - \tilde{\beta}) \sin \tilde{\beta}, \tag{18}$$

$$r_3 = r_1 \sqrt{2} \sin (45^\circ - \tilde{\beta}) \cos \tilde{\beta}, \tag{19}$$

$$e = \frac{r_1}{2} \sin 2\tilde{\beta}. \tag{20}$$

Formulas (11)-(20), produced by Tsander, in combination with the expression defining flight time [2, p. 472] allowed him to calculate the elements of the elliptical path of the rocket and the kinematic parameters of its motion for flights to ranges of up to 20,000 km (on the assumption that the flight followed the optimal trajectory TME) [2, p. 460].

Stating and solving the problem of optimization of the flight conditions of a rocket over an assigned range, Tsander utilized the quantitative estimation of the results produced, studying the problem of providing the necessary reserves of fuel on board the rocket.

Assigning the values of range (S), using formula (11), Tsander utilized the $\tilde{\beta}$ thus produced to determine the corresponding values of B (12) and then, using formula

$$M_0/M = e^{V/W} \tag{21}$$

produced the values of M_0/M. He constructed the function $M_0/M = f(S)$ for "oxygen" and "hydrogen" rockets, using the corresponding exhaust velocities of the combustion products.

Of course, using formula (21) to construct the function $M_0/M = f(S)$, Tsander kept in mind the relative accuracy of determination of M_0/M, resulting from the limitations of applicability of this formula, and therefore he calls the functions $M_0/M = f(S)$ thus produced the "limiting" low curves relative to fuel reserve [2, p. 457, 458, 476]. These functions he looked upon as standards for comparison with dependences constructed

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considering the thermal efficiency of the rocket and specific flight plans and, in particular, when the necessary quantity of fuel components was stored fully on board the rocket and when the oxidizer was (fully or partially) taken from the atmosphere [2, pp. 457, 458].

Analyzing the results produced by Tsander and keeping in mind the statements of Tsander himself noted above, we can formulate the basic statements characterizing his views of the possibility and conditions of realization of long and superlong range flights as follows.

The energy reserves necessary to fly around the Earth are not much greater than the energy expenditures required to fly around a fourth of the terrestrial sphere. This indicates the great economy of superlong range flights. To fly over one fourth of the Earth, a rocket requires 83% of the energy necessary to fly over one half of the Earth. The energy expenditures of flight around the Earth and flight over a range equal to half of the circumference of the Earth are approximately the same [2, p. 479].

For flights over a range of 20,000 km (half of the circumference of the Earth), in the case of fuel stored fully on board the vehicle, the fuel mass must represent 85% and 95% of the total mass of the rocket (for "hydrogen" and "oxygen" rockets respectively).

Partial utilization of the oxygen in the surrounding atmosphere significantly improves the payload capacity of the rocket.

With partial (or particularly with complete) utilization of atmospheric oxygen as the oxidizer, flight around the Earth does not require the use of metals as fuel [2, p. 481].

In order to determine specific plans for flight the reality of the achievement of superlong range flights increases if we consider the rotation of the Earth [2, p. 481].

These are the primary aspects of the "purely technical" theoretical-calculation development of Tsander concerning the flight dynamics of ballistic rockets.

2. Going over to the characteristics of the works which in the 1920's and 1930's analyzed problems similar to the problems discussed in Tsander's work of 1932, we must note that the statement of the problem of studying the free motion of a body in a central field of gravity in and of itself has a rather extensive history. Having no opportunity to analyze the corresponding investigations in detail, we note simply that work on classical mechanics, astronomy and the ballistics of artillery shells were among the stages in the history of analysis of the

the problem of free motion in a central field of gravity [3-7].

The works of Cranz and Charbonnier, in which the flight of an artillery shell in airless space at high velocities is looked upon as the limiting case for artillery, come into contact with the problems which later became the subject of the investigation of the ballistics of LRBM [6, pp. 91-106; 7, pp. 22-29].

Charbonnier and Cranz composed differential equations for the motion of a shell in a central field of gravity, ignoring the resistance of the air. They also studied the problem of the conditions of flight of a shell such that when they are observed, motion can be realized over a conical-type trajectory (circular, elliptical, parabolic and hyperbolic). However, since the assumption of zero air resistance was quite strong for artillery practice, and the possibility of fulfillment of the conditions under which an artificial body might move at orbital velocities had not been studied by the specialists, these investigations were, /45
it seemed at the time, purely theoretical, with no practical purpose. Nevertheless, the problem of the determination of the conditions required for flight over various conic section trajectories was solved on a mathematical basis. The problem of determination of the elements of the trajectory, like the problem of development of calculation systems relating the initial conditions of flight to the geometric characteristics of the trajectories, remained unsolved.

It is understandable that the statement and solution of these problems corresponded to studies of a more practical nature, first undertaken by scientists involved in the area of space flight.

Thus, as early as 1923, Oberth studied the case of free motion of a rocket in a central field of gravity [8, pp. 30-30]. Under the assumptions which he made, the trajectory of flight of the rocket was an elliptical curve. Due to the statement of the problem used in this work, Oberth did not analyze a range of problems related to the solution of the basic ballistic problem[1], but merely established the quantitative relationships between energy expenditures required for travel of a rocket over a sector of an elliptical curve from one altitude to another.

However, in this work, the question of the trajectory of free flight was studied as applicable to an apparatus capable of achieving (satisfying) those initial conditions for which the trajectory of motion can be represented as an elliptical curve. It is probably only from this point of view that the results of

[1]The basic problem of ballistics is determination of the elements of the trajectory and the primary characteristics of motion of the rocket based on assigned target data.

Oberth can be looked upon as more positive than the results of Charbonnier and Cranz, since in their analytic aspect the results of Oberth repeated the results of the investigations of the earlier specialists.

In the second edition of his work in 1923[1], the solution of the problem of the motion of a rocket in a central field of gravity was not changed, whereas in a work published in 1929, Oberth discusses the statement of the primary problem of ballistics. In this work, he presents a rather complete mathematical apparatus for elliptical theory, as well as calculation dependences which can be used to determine the primary trajectory elements, produces a formula for the range of flight of a rocket and, which is particularly important, solves the problem of planning optimal trajectories [9, pp. 113-115]. In a word, Oberth's work of 1929 reflects problems quite similar to the problems which we discussed above in our analysis of Tsander's work of 1932.

One year later, in 1930 in Paris a work by Esnault-Pelterie was published, in which a range of problems relating to the solution of the primary ballistic problem of the motion of a rocket in free flight is solved in a stricter mathematical form than in the work of Oberth of 1929. This work presented the results of concrete calculations to determine the flight parameters of medium and long range rockets [10, pp. 42-48, 158-162]. /46

Among the most significant results of the investigations of Oberth, Esnault-Pelterie and Tsander is the solution of the problem of planning optimal trajectories and developing calculation plans for determination of the kinematic and geometric parameters of motion of a rocket during the passive sector of the trajectory.

These problems were discussed in the works of these investigators to a varying degree. Thus, the theoretical portion, particularly the mathematical apparatus of the application of elliptical theory, was more broadly and strictly presented in the work of Esnault-Pelterie. He quite elegantly solved the problem of determining the relationships for calculation of the velocity and angle of insertion in the case of flight over an optimal trajectory [10, p. 48].

Tsander's work presented an engineer's interpretation of the application of the elliptical theory of motion. Tsander particularly studied the problem of the area of existence of

[1]Unfortunately, we were not able to obtain an original copy of the second edition of Oberth's work of 1923. Nevertheless, analyzing the discussion of this work by N. A. Rynin [11, pp. 147-148], we can conclude that the work of 1925 is a simple republication of the work of 1923.

an optimization problem in planning trajectories requiring minimal energy. Tsander presented the most orderly engineering interpretation of the results of ballistic calculations, which quite naturally led him to the statement and solution of problems related to the selection of the plan parameters of a rocket. In the work of Oberth [9], there are no calculations whatsoever, while the theoretical portion, concerning the application of elliptical theory to the design of optimal trajectories, is inferior to the related materials in the works of Tsander and Esnault-Pelterie. Nevertheless, we should note that the results of the solution of the primary problem of ballistics were published in 1929 by Oberth for the first time, though quite schematically.

The exceptionally unfavorable circumstances under which the pioneers of astronautics had to publish their works represent a generally known fact. In this connection, it is interesting to analyze the history of the statement and solution of the problems of the flight dynamics of ballistic rockets in the creative works of the investigators we have mentioned, since it is quite clear that under the circumstances we have mentioned the moment of publication of results of an investigation might lag considerably behind the completion of the investigation itself.

At the present time, we do not have sufficient materials to draw conclusions concerning the period of development of the problems of the dynamics of LRBM flight dynamics by Oberth and Esnault-Pelterie. Our familiarity with a number of the published documents from the Tsander archives, however, indicates quite clearly that he stated and solved the problems of the dynamics of LRBM flight long before publication of his work of 1932. One direct indication that the range of problems studied by Tsander in his work of 1932 was actually solved by 1927 is the formulation of a special section of his book, which Tsander intended to publish under the title "Flights to Other Planets; a First Step into Uninhabited Space, the Theory of Interplanetary Voyages." The title of the sixth section of this unpublished work of Tsander is more than descriptive: "Calculation of the Flight of Rockets Encircling a Large Portion of the Terrestrial Sphere. Minimum Velocities which Must be Imparted to Rockets to Achieve a Given Flight Range. Numerical Data"[1]. This formulation leaves no doubt that by the moment he decided upon the title of this book, an application for publication of which Tsander sent to the Scientific Section of Glavnauka in 1927, he had studied the problem of planning minimal energy trajectories. /47

[1]The title of the book Perelety na Drugiye Planety.. is based on the text of an announcement written by F. A. Tsander [13, p. 87]. The conspectus of the book "Flights to Other Planets..." from which the title of the sixth section is presented can be found in [1, pp. 444-455].

Since materials have been preserved in which Tsander discussed the essence of the problems which he solved concerning LRBM flight dynamics rather completely, we indicate the year of 1927 as the year in which Tsander solved the problem of planning of TME. The earlier archive documents of Tsander also contain references to work which he performed on rocket flight dynamics. The formulation of the documents indirectly indicates that the level and volume of the development performed by Tsander before 1927 essentially corresponded to the materials of the work of 1932.

For example, in 1924, in an abstract of a speech made at Moscow State University in October of 1924, Tsander, in a section with the remarkable title "...The Military Significance of Interplanetary Flight," delineated the following subsections: "...Range of Interplanetary Flights," "Velocity of Long Range Flight" [13, p. 49]. In 1925, in the chapter titles of a book (also unpublished) entitled "Flights to Other Planets and to the Moon," in the section "Works of the Author," Tsander included the point: "...Possibility of Rapid Long Range Flights" [13, p. 54]. As an independent section, Tsander proposed to present in this book materials illustrating "...The Application of High Velocities to Military Affairs: Long Range Cannon, Long Range Rockets..." [13, p. 54]. And, finally, in 1926 in a description of his original works which he sent along with his first application to Glavnauka, of 8 October 1926, Tsander directly stated that he had prepared materials on the calculation of "...Long Range Rockets" [13, pp. 83, 84].

3. We must approach the problem of technical evaluation of the results of the investigations of Tsander on the theory of LRBM flight in full consideration of the actual capabilities of an individual scientist, working almost a half century ago. Now, the level of development of even individual problems in the area of LRBM flight dynamics is determined by the goal-directed efforts of many teams of specialists. Therefore, our evaluation of Tsander's work should be conducted, keeping in mind contemporary developments, performed in the preliminary stage, in particular in the stage of sketch planning.

As we know, the method of planning of ballistic calculations should allow, without requiring cumbersome calculations and numerical integration, rapid determination of the flight characteristics of a rocket on the basis of its design parameters and the reverse: based on assigned flight-tactical characteristics -- the design parameters.

If we turn to the calculation and theoretical developments of Tsander, we can show that the plan developed by Tsander (with some additional simple relationships) solves most of the practical problems which make up the basis of contemporary planning of ballistic calculations. Let us list these problems.

1. Given the velocity, altitude and angle at the initial point of the passive sector, find the range.

2. Given the range, height and angle at the initial point of the passive flight sector, find the velocity.

3. Given the range and height of the initial point of the passive sector, find the optimal angle, requiring the minimal velocity.

4. Given the altitude and velocity at the initial point of the passive sector, find the optimal angle, assuring the maximum range.

The calculation plan developed by Tsander allows the flying-tactical data given in these problems to be related to the selection of one important design parameter M_0/M. /48

In order to describe the level of the design development of Tsander, the results of his calculation are presented, together with the results of similar calculations published in a contemporary work on flight dynamics of rockets [12, p. 235].

In view of the good agreement of the results of the calculations compared, in order to confirm (illustrate) this we cannot use the traditional graphic method, and therefore present the results of the calculation in table form. The table presents the calculated values of maximum trajectory height h, velocity at the beginning of free flight V and flight time t, calculated for rockets with various flight ranges. In the lines labeled 1 and 2 we see the values of these parameters based on the data of (respectively) Tsander and current-day calculations, arbitrarily taken as the standard. Since the calculated values of the parameters h, V and t in the work of Tsander for range $\alpha = 30°$ and in [12] for range $\alpha = 120°$ are not presented, we calculated these parameters for these ranges in accordance with the formulas presented in each of the two works. The values of the parameters produced as a result of this calculation are marked with a plus sign.

	Range					
	30°	60°	90°	120°	140°	180°
			h, km			
1	714+	1165	1320	1165	895	0
2	717	1167	1321	1167+	898	0
			V, km/sec			
1	5,0+	6,14	7,18	7,6	7,75	7,5
2	5,07	6,46	7,2	7,65+	7,73	7,9
			t, min			
1	15,9+	24,9	32,2	37,8	40,2	42,3
2	15,9	24,9	32,2	37,8+	40,2	42,2

Comparison of the calculated values of the parameter h, V and t produced Tsander with the data from the standard calculation indicates rather convincingly the identical nature of the formulas used to calculate these parameters; the slight differences which can be noted in the values of some individual parameters are explained by the use in the calculations of geophysical constants (for example, R of the Earth, g) which, of course, differ somewhat in these calculations.

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THE PROBLEMS OF THE INVESTIGATIONS OF F. A. TSANDER IN THE AREA OF SPACE TRAJECTORIES AND PUBLICATION OF HIS WORKS

A. F. Tsander

A number of the basic statements of contemporary astrodynamics were set forth and scientifically founded by F. A. Tsander. However, this has not been reflected in the literature, which is explained to a great extent by the delayed publication of the research of F. A. Tsander. Also, the lack of scientific analysis of many of the fundamental works of Tsander is significant here.

A significant portion of the works of Tsander on astrodynamics has been combined and published in one work: Polety na Drugiye Planety (Teoriya Mezhplanetnykh Puteshestviy) [Flights to Other Planets (Theory of Internplanetary Voyages)] [1, pp. 285-360; 2, pp. 277-359]. The theme of these works is that of space ballistics; they were undertaken by Tsander during the first half of the 1920's, i.e., before publication of the investigations of other authors on this same theme. The works of K. E. Tsiolkovskiy [3-5], R. Goddard [6] and G. Oberty [7] published up to that time contained no calculations of the trajectories of flights to other planets. As concerns Esnault-Pelterie, we must note that although in his work published in 1913 [8] he gave the results of calculations of the flight times to Mars and Venus, he based his results on the assumption of even, straight-line movement of the spacecraft (SC) at 10 km/sec, i.e., analyzed a high velocity, corresponding to great fuel consumption, and did not consider the influence of solar gravitation on the motion of the spacecraft.

Among the calculations of F. A. Tsander included in his work mentioned above we encounter many similar to those published by other authors but much later (after the death of F. A. Tsander).

Many results produced by Tsander were proven by him and illustrated using slides in his special and public lectures held in Moscow (1924-1925), Khar'kov (17 October 1924), Leningrad (17 November 1924), Saratov (January 1925), Ryazan' (November 1925) and Tula (December 1925)[1]. One of the works from Polety na Drugiye Planety (Teoriya Mezhplanetnykh Puteshestviy) was presented by Tsander at Glavnauka in 1926 [17], while the others, in his notebooks written in ordinary (non-shorthand) script, were mentioned in his application to the Scientific Department of Glavnauka of 8 October 1926.

[1]The materials for a number of lectures and reports by Tsander, particularly the slides, were published in 1967 [9]. The original copies of many of the materials for his lectures are presented in the Archives of the Academy of Sciences USSR (for example, [10-16]).

We present below the results of the scientific analysis which we have performed of the works of Tsander mentioned and their comparison with the works of other authors. In those cases when the works of othe authors on this same theme were published during Tsander's lifetime, this is particularly noted. /50

I. In the work "Determination of the Paths of Flights, Additional Velocities which Must be Imparted to an Interplanetary Spacecraft by its Rocket, and Flight Durations" [18; 2, p. 277], Tsander presented an analytic group of the energetic optimality of space trajectories in the form of tangential ellipses and semiellipses, i.e., elliptical trajectories touching the orbits of two planets. It was undertaken on the assumption of circular coplanar orbits.

After Tsander's death (in 1935), Esnault-Pelterie published ananalytic proof of the energetic optimality of tangential ellipses which was different in form from that of Tsander, but actually was quite similar to it [19]. We note first of all that the formula of Esnault-Pelterie for the velocity impulse necessary to transfer the spacecraft from a circular orbit to an interplanetary elliptical trajectory is essentially identical to formula (17e) of Tsander, published for the same value in [18][1]. To compare these formulas, we must consider the difference in symbols used. In both formulas, the velocity impulse is expressed through the ratio of absolute values of radius vectors of the perihelion and aphelion to the absolute value of radius vector of the spacecraft at the point of the heliocentric launch.

Furthermore, the derivatives dz/dr_p, dz/dr_a of Esnault-Pelterie of quantity z, proportional to the square of the velocity impulse, coincide to the derivatives du/da of Tsander with an accuracy to a constant factor where $\gamma > 1$ and where $\gamma < 1$ respectively (u is proportional to the square of the impulse of velocity, a is the length of the semimajor axis of the ellipse, γ is the ratio of radii of the planetary orbits).

At the present time, as we know, interplanetary trajectories in the form of tangential ellipses are called Hohmann trajectories in honor of the German scientist W. Hohmann who published the results of calculation of these trajectories late in 1925 [20]. However, the results of similar calculations of flight over tangential ellipses for the cases of a flight to Mars and a flight to Venus can be found in the manuscript of Tsander, which he wrote in April of 1923 [21; 9, pp. 10-14], in 1924-1925 they were reported and demonstrated by him by means of slides [9, pp. 24, figure 4, 6]. The stenographic records of Tsander

[1]For example, see [2, p. 301].

include calculations relating to tangential ellipses as early as 1921 [22]. Furthermore, Hohmann did not present an analytic proof of the energetic optimality of tangential ellipses. It is for this reason that in 1969, i.e., 40 years later, in a large review article on impulse trajectories it was stated that the optimality of these trajectories remained no more than hypothetical until quite recently [23, p. 809]. The opinion of Hohmann that tangential ellipses were quite obviously the most fuel-economical space trajectories was erroneous, since even for proof of the favorability of tangential launch of a spacecraft from a circular orbit in order to overcome completely the attraction of the center of gravity one must perform certain mathematical operations: application of the law of conservation of energy and construction of a triangle of velocities, with investigation of the dependence of the velocity impulse on the angle between the circular velocity and the velocity of the spacecraft after the velocity impulse is imparted to it. If the trajectory lies fully within the sphere of influence of the center of gravity, the final velocity remains undetermined, which complicates the analysis. /51

Analytic proof of the optimality of tangential ellipses was undertaken by Esnault-Pelterie after the publication of the book of Hohmann and after generation of this proof by Tsander. In 1928 in a published work, Esnault-Pelterie presented calculations of the flight time to Venus and to Mars produced earlier [8], and in a book published in 1930, made the following statement concerning them: "These figures are quite arbitrary, since a tually the orbits must be analyzed considering solar gravitation. These works were undertaken by Hohmann and Pirquet. The length of the flight produced by them is significantly greater than the figures here presented" [24, p. 204].

The work of Tsander in question also discussed rapid transfers and presented calculations concerning flights on a parabola.

II. In the work "Determination of the Neutral Position of Planets Based on the Time of Departure and Arrival"[1] Tsander presented the theoretical principles of determination of launch windows, based on energetic considerations [25; 2, p. 307]. These calculations were not to be found in the works of Hohmann.

III. In the work "Determination of Paths for Flights in World Space with Return to the Earth After a Whole Number of Years" [26; 2, p. 355], Tsander suggested and investigated a special type of encounter trajectory, presently called a modified Crocco trajectory. Some of these trajectories, as well as those currently called Crocco trajectories (which can be considered a particular case of the "modified" Crocco trajectories),

[1]Chapter titles presented in abbreviated form.

Tsander demonstrated using one of his slides [9, p. 25, figure II] at his lectures and reports in 1925 in Tula [27] and at State Aviation Plant No. 4 [28], together with the corresponding results of calculations. Crocco, many years after the death of Tsander, independently repeated his suggestion. The report of Crocco, in which he suggested there one-year trajectories, was published in 1956 [29]. On the whole, Tsander's investigation was more general in nature, encompassing an entire class of trajectories. Crocco, however, performed additional investigations on one-year trajectories, refining and presenting more detail concerning individual theoretical statements. This is not surprising, since Crocco worked in the period immediately preceding the launch of the first spacecraft, requiring more detailed development.

IV. In the work "Change of the Path of a Flight Around the Sun by the Action of the Planets" [30], Tsander not only suggested the use of the gravitational field of the planets and their satellites in order to accelerate or decelerate a spacecraft (currently called a gravitational maneuver), but also provided a theoretical foundation for this suggestion. The method of investigation of this question developed by Tsander presents a number of formulas which are classic in our own time. But Tsander went further than investigation of the effect itself. He stated and solved the very important problem of the comparsion of direct flight to other planets with flight utilizing this effect. Tsander demonstrated some of the results of his calculations in his lectures and reports. The suggestion of utilizing the gravitational field of the planets was first published in 1929 in the autobiography of Tsander, included in the book of N. A. Rynin [31]. At this time, no other such work had yet been published.

V. In his work "Adjustment of Flight" [32], Tsander, long before attention was turned in print to the problems of adjustment of the initial planned trajectory, stated and mathematically /52
investigated the problem of the optimal correction impulse in the simplest case of coplanarity of the initial and corrected trajectories. In this work, he presented the valuable idea of defining a space trajectory by means of the radius-vector of the spacecraft and its velocity. Based on this idea, extended to the case when the radius vector and velocity are fully assigned as vectors, Gobetz and Doll in 1969 classified all impulse trajectories [23].

VI. In his work "On the Suitability of Acceleration of the Flight of a Rocket at Moments when the Flight Velocity is Still Great" [33], Tsander set forth and provided a mathematical foundation for the thought of the expediency of acceleration of the flight of a rocket vehicle at high velocities under conditons such that it is necessary to overcome the gravitational attraction of a celestial body around which flight was initially performed.

The work was presented to Glavnauka in 1926 [17], when such works had never yet appeared in print; however, the main idea of this original work was published in the autobiography of Tsander in 1929 [31]. The mathematical statement of the problem set forth by Tsander, based on comparison of the velocities of the spacecraft at some distance from the center of attraction, allows some generalization. This generalization, including comparison of the velocities of the spacecraft not only as to absolute value but also as to direction, makes possible the analysis of the directly opposite case, when it is desirable to come as close as possible to the center of gravity. The method of Tsander, thus generalized, leads to optimal intercept trajectories of two types: tangential ellipses with impulse imparted to the vehicle in the direction of initial movement at the pericenter (when moving away from the center of gravity) and to tangential ellipses with a change in velocity before the initial motion at the apocenter (upon approaching the center of gravity). At the present time, both of these methods of changing the velocity of spacecraft are widely used.

In addition to what we have already noted, let us make a few additional comments.

1. Analysis of one of the slides of Tsander [9, p. 24, figure 5] leads us to the conclusion that Tsander studied the possibility of reducing the time of a flight to Mars without greatly increasing the consumption of fuel and achieved a positive result, according to which in order to achieve this purpose one must fly along an ellipse which is near tangential. The same conclusion was reached in his time by the Austrian engineer Guido Pirquet. He published in 1928 [34] specific trajectories for flights to Mars and Venus which he produced on the basis of original graphic investigations. However, we must note that according to the notes on the slides, written by Tsander on 1 July 1925, the slide in question was prepared by Tsander before this date and, consequently, before Pirquet. The idea of flight on an ellipse which is near tangential was used for the first interplanetary space flight of a domestic interplanetary space station, Venera-1.

2. In many of his works, Tsander used the approximate method of reducing a complex problem of many bodies to sequential solution of two-body problems -- a method which is quite progressive. For example, the determination of various types of trajectories for flight around the moon in a geocentric system of reference can be considered a development of the ideas and methods used by Tsander in his work on the gravitational maneuver [30].[1]

[1]Actually, either of these trajectories corresponds to the flight which Tsander studied by a hyperbola in a selenocentric system. Tsander also presented the idea of transition between a geocentric and selenocentric system of reference, using the method of velocity triangles.

3. Formulas (3), (5)-(3), (6) form the minimal velocities necessary to reach the moon, presented by V. A. Yegorov in 1957 [35], are actually one of the applications of formulas (12) and (14) presented by Tsander in his work "The Flight of Long-Distance Rockets Outside the Atmosphere" [36; 2, pp. 463-464]. /53

4. Tsander indicated the desirability of differences in the design of spacecraft leading to an orbital station and smaller spacecraft departing from it, depending on their purpose. In particular, he suggested the simplest form of descent apparatus, the glider [14, 37].

5. It follows from what we have said in parts I-VI (see above) that Tsander had studied impulse trajectories belonging to all three possible types: intercept, transition and capture.

The cycle of works of Tsander "Flights to Other Planets" belonged, essentially, to a new division of astronautics -- space ballistics. Based on the investigations performed, we conclude that this was a work of significant content, encompassing the broadest range of problems in this area for his time. It should be noted that Tsander's appearances were essentially the first timely publications on space ballistics, if we take the concept "publication" in its broadest sense, including not only the actual publication of works, but also public appearances.

The public appearances of Tsander were reflected in the press to some extent. In particular, N. A. Rynin in his book published in 1929 [31], before the autobiography of Tsander gave his work high marks, clearly having in mind the volume extending beyond the framework of the articles published by Tsander in 1924, dedicated to the basic plan of the spacecraft and placed by Rynin before the autobiography. Rynin wrote, "Due to the valuable works of Tsander in the general area of interplanetary voyages, it is interesting to familiarize ourselves with the conditions of work and life of this engineer" [31, p. 190].

Since Tsander had sent none of his works to Rynin, the information which Rynin had on the "works of Tsander in general" could have been obtained only by listening to his public appearances. Most probably, Rynin, who lived in Leningrad, was present at some of the appearances of Tsander held in this city. In the autobiography of Tsander, as we know, there are references to his appearances (in particular in Leningrad), and the statement that he is writing a book of some 500 pages.

Professor Vetchinkin has also confirmed the facts of the speeches of Tsander. In particular, in response to the works of Tsander sent to Vetchinkin from Glavnauka, he even suggested that quite possibly the work of Hohmann "may have been influenced

by what he had heard concerning the reports of F. A. Tsander presented in the winter of 1924/1925" [38]. But since Tsander attached to his application to Glavnauka 17 copies with his slides, which he showed during his lectures and reports, and a conspectus of his presentations, actually Vetchinkin confirmed the content of Tsander's appearances.

Naturally, the question may arise as to whether the appearances were known to Hohmann.

In analyzing this question, we must turn our attention to the fact that the idea of the optimality of tangential ellipses (as to fuel consumption) was first published not by Hohmann, but rather by M. Valier [39]. The two authors had met and referred to each other in print, but neither of them made any /54
reference to the public appearances of Hohmann which, if they existed, would have been quite significant. Hohmann, in the foreword to his book, reported only that he began working on the problems related to space flight some 10 years earlier. However, this simple statement does not do anything to disclose the dates of the beginning of which work on tangential ellipses.

A number of other facts indicate the independence of the work of Tsander concerning space ballistics, the fact that their conduct did not depend on the work of other authors. Let us list some of these facts.

1. Tsander had no contacts with foreign scientists, which was reflected in the review of Vetchinkin mentioned above, well known to Tsander. The appearance of the book of Hohmann was unexpected for Tsander. It is also characteristic that among the lists of persons involved in interplanetary voyages made up in 1926 for K. E. Tsiolkovskiy by A. B. Shershevskiy, Tsander's home address was not listed, whereas the addresses of both Oberth and Hohmann were listed, as well as those of Vetchinkin and Rynin [40, pp. 126, 127].

2. The stenographic records of Tsander include highly detailed information on the times that he worked recorded, indicating even the hour and minute, and are generally in the nature of a daybook, which can be used step by step to establish how any given idea, method of calculation, etc. arose in Tsander's mind.

3. The extreme conscientiousness, attentiveness of Tsander in relationship to other authors, which is indicated by many facts. In particular, in his presentations he popularized not only his own works, but quite frequently the works of Tsiolkovskiy, Oberth and Goddard. He stated that he was familiar with the work of Tsiolkovskiy published in 1903, before the beginning of his own investigations. He edited the works of Tsiolkovskiy and Oberth even when time was extremely short, etc. Tsander was

distinguished not only by his great orderliness, but also and primarily by his unlimited, selfless enthusiasm in the area of interplanetary voyages. This gives us cause fully to believe all of his statements in which he calls certain works his own, thus indicating that he wrote them. In particular, in the "resume" of a report which he presented on 20 January 1924 at the Theoretical Section of the Moscow Society for Astronomy Enthusiasts, he wrote, "Then presented own calculation of minimal and total additional velocity which must be imparted to interplanetary spacecraft after they overcome the attraction of the Earth to reach the nearest and other planets" [12].

In the autobiography published by Rynin, Tsander also wrote of his work on flights to other planets.

A number of materials by Tsander indicate that he desired to publish his works in rather complete form, but did not succeed in so doing. In particular, the results of his calculations concerning flights on tangential ellipses were contained in one version of his article "Flights to Other Planets," written in 1923 and ending with the words, "Continuation follows" [41, 42], in the article "On Flights to Other Worlds," written in August of 1924 [43]. We have already noted his application to Glavnauka [17, 44-47].

In the 1920's, Tsander published primarily works concerning the plan for his spacecraft or, as he called it, his interplanetary spaceship-aeroplane, and rather briefly at that (the article "Flights to Other Planets" of 1924 [37]). It was plans for spacecraft which were discussed in the first half of the 1920's with the greatest animation, and in this case Tsander correctly followed this problem as the most important. We note that interest in these plans also had practical significance, /55
since in addition to some fantastic and unrealistic elements in the plans, they stimulated engineering thought in this area and began the approach to the simplest initial problems of rocket technology. For example, Tsander first performed thermal design of an LRE for the engine of his interplanetary spaceship-aeroplane [48; 11, p. 28].

Beginning in 1928-1929, the center of gravity of the works of Tsander shifted significantly in the direction of rocket-engineering themes, most pressing at the time in the sense of the approach to the realization of rocket flight. The problems of publication of investigations on space trajectories, in connection with this, were set aside for an indefinite time. Beginning in 1932, Tsander published a book [49] in which these investigations were not even reflected.

In conclusion, based on what we have said, let us note quite briefly some of the conclusions related to the problems of priority.

1. We can consider with good foundation that works on tangential ellipses were performed by Tsander independently of Hohmann and these trajectories are objectively connected not only to the name of Hohmann, but also to the name of Tsander.

2. The analysis of the question of reducing the time of flight to Mars was made by Tsander independently of Pirquet and by another method. Although the studies of Pirquet were more detailed, the general conclusion concerning flight on ellipses near tangential, following from the work of Tsander, is identical to that of Pirquet.

3. The so-called modified Crocco trajectories and "Crocco trajectories" were generated and refined by Tsander long before the presentation of Crocco, which occurred many years after the death of Tsander.

4. Tsander has priority on the idea of the gravitational maneuver (published in 1929, reported still earlier) and its development.

5. The idea of imparting a velocity change at the pericenter to move further away from a center of gravity was set forth by Tsander independently of other authors. The work was published practically simultaneously with their work.

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11. Archives of Academy of Sciences USSR, Folio 573, List II, File 1, No. 21.

[1]Since the materials of F. A. Tsander in the Archives of the Academy of Sciences USSR are currently being processed, references are given in two old forms: the form composed by V. N. Raninskiy of 15 March 1951 (represented as list I) and the form composed by A. F. Tsander (list II); in the latter case, the word "file" is abbreviated as "f."

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13. Archives of Academy of Sciences USSR, Folio 573, List II, File 1, No. 72, No. 73, No. 75a. /56

14. Archives of Academy of Sciences USSR, Folio 573, List II, File 1, No. 8.

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THE WORKING JOURNAL OF F. A. TSANDER AS A HISTORICAL SOURCE

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In scientific-history research, study of the creative process, style, creative laboratory of scientists, designers and engineers play an important role. Each one follows his own path: problem -- idea -- search for possible versions of the solution of practical problems -- determination of the optimal version -- planning. /57

Investigations of the creative path of F. A. Tsander are based on documentary sources. In recent years, new materials related to the life and activity of the scientist have become available to the scientific community, including his working journal [1]. The value of this document as a historical source is beyond doubt. The entries flow almost without interruption from 5 September 1930 to 5 August 1932. Laconic and quite businesslike, they carry a large volume of information concerning a period in the life of Tsander which was quite important, encompassing the beginning of his experiments with the OR-1 engine, tracing the activity of Fridrikh Arturovich during the period immediately preceding the creation of the Group for Investigation of Reaction Motion (GIRD) as a part of the Central Council of Osoaviakhim USSR, as well as the GIRD period -- from the creation and first steps of the group to the development of practical work at the GIRD experimental-production base. The journal discusses the various aspects of the work, reflects events and facts related to the development of plans, activity on their achievement, the conduct of experiments. Events of an organizational nature are recorded, many persons who were variously related with the work in the area of reaction technology are mentioned. The journal discusses widely varied aspects of the work performed, allowing us to gain a better understanding of the thinking and the significance of the events of those years, their interrelationship and dynamics, more fully and accurately interpreting a number of important documents.

We should note particularly that the working journal of Tsander must not be looked upon as any sort of memoir. Here we find no entries concerning the personal experiences of the author, no author's commentaries, evaluations or summaries. Is this a shortcoming or an advantage? In our opinion it is an advantage. A written source of this type, in addition to objective information, quite frequently carries subjective evaluations by the author. This is found in his commentaries, the emotional tone of the presentation, the listing of individual features, the accent on individual aspects of events and creates before the investigator a sort of subjective-logical barrier. The source

which we are currently discussing is not a record of Tsander's experiences, but rather a unique working report concerning the achievements of the day, something like a time schedule of the working day. The journal contains a separate column noting how much time was spent on various specific tasks, specially denoting and accounting for the time spent on "work on the r. e." (reaction engine).

Another advantage of the working journal of Tsander is the fact that events were recorded immediately after they occurred. This is quite important, since details are not lost which are frequently omitted in documents written some time after the event; the information is more reliable, the chronology is more accurate. /58

There is no doubt that the journal belonged to Tsander or that he wrote it in his own hand. This is confirmed by comparing the entries in the journal with other documents of Tsander, the authorship of which has been precisely determined.

In order to check the reliability of the information, a number of entries from the journal were compared with documents, the reliability of the content of which and the dating of which were beyond doubt. Identity was established in all cases.

Due to the records in the journal, it is possible to establish the chronological framework of certain events. This was the case with the founding of GIRD, as was discussed at the first Tsander readings [2, p. 92]. Another example. We know that Tsander made a supplement to the agreement with the Bureau for Air Technology of the Central Council of Osoaviakhim of 18 November 1931. According to this agreement, he was to plan and develop working drawings and perform experiments on an experimental reaction engine, the OR-2, and the RP-1 rocket plane [3, sheet 10]. Somewhat later, Tsander adds a supplement. Its text is known: in addition to the above, he presented the basic diagram of the entire installation, its design scheme, detailed development of the nozzle, tanks, ignition system, etc. However, this document is not dated [4]. In the journal, however, there is an entry: "27/11 -- 31...Visited Central Council of OAKH, made application and signed supplement to agreement."

In certain cases, the entries in the journal help us to fill in gaps in our knowledge concerning events and how they occurred. Thus, we know of the order of R. P. Eideman of the CC Osoaviakhim of 14 July 1932, which confirmed the current existing structure of GIRD (TSGIRD) and precisely defined the tasks of the group, which were complex in nature [5]. Some additional data on the preparation of this order are provided by Tsander's journal entry of 10 July 1932 concerning a meeting in Eideman's office. It includes significant information; this is the entry: "21/7 -- 32...Meeting on report of section III." The

task of this section of GIRD included organizational-mass and propaganda-popularization work. The names of the participants in the meeting are not included, but the very fact of the committee approach used to perform this task indicates the significance which was attached to this area of the work by GIRD.

In a number of cases, the journal helps us to determine the areas in which we should look for sources. This can be said concerning the as yet unfound records of the experiments with the OR-1, the significance of which can hardly be overestimated. We find that they existed in more than one copy. In the entry of 19 April 1932, in addition to other work, we find: "...write copies of reports on experiments with OR-1." This entry was made by Tsander the day before he was transferred from the Institute for Aviation Motor Building (IAM) to GIRD. It is quite possible that before his transfer he removed the copies with the documents needed, and the originals of the reports, as working materials, were placed in the fund of technical documents of IAM. This makes sense of the search process.

In general, the study of brief extracts from the journal can yield very interesting results. One example is the information thus produced on one of the earliest experimental installations of Tsander, the unique stand for flame testing of combustion chambers.

On 3 and 29 April of 1931, Tsander records that certain problems concerning experiments with OR-0 were discussed by him and Krutikov. Engineer N. S. Krutikov in the early 1930's worked in the propeller-motor section of the Central Aerohydrodynamic Institute (TSAGI). The Archives of the Academy of Sciences USSR contain his recollections on his joint work with Tsander [6, sheets 67-68]. Krutikov reports that Tsander "...performed experiments in the propeller motor section on the combustion of a gasoline-air mixture in a small chamber to which a Laval nozzle was attached," that the installation consisted of two internal combustion engines, one of which was used as the driving engine, the other as a compressor. /59

Just this same sort of installation is reported in the recollections of mechanical technician M. P. Shukhtirev; he installed it at TSAGI in 1930 [6, sheets 41-42]. Two internal combustion engines, a de Dion Bouton (driving) and Brazier (driven, operating as compressor), were installed on massive wooden beams. However, the compressor, as Shukhtirev writes, "...was used to compress not pure air, but rather air mixed with gasoline, because the air was drawn in through a carburetor, to which gasoline was supplied from a tank.... However, this mixture was not ignited in the cylinders, but rather blown out through the exhaust valves.... At the end of the exhaust pipe, a combustion chamber in the shape of a pear was attached by a flange. It was in this chamber that the fuel mixture was ignited.

Ignition was by an ordinary electric spark plug.... The exit from the chamber was through a reaction nozzle.... Before the nozzle was installed a special scale with a disc. The disc was perpendicular to the stream of flame exhausting from the nozzle. The thrust was thus measured through a system of levers.... The reaction jet was pulsating, since it was a four cycle motor" [6, sheet 41, ob]. Shukhtirev writes that, in spite of the imperfections of the installation, Tsander was delighted [6, sheet 42]. His recollections also include a diagram of the installation.

The experimental method is described the same way by Krutikov, who reports that "...each new portion of the mixture was ignited by the remaining hot gases already present in the combustion chamber or by the heated walls of the chamber, which became cherry red by the end of the experiments." He adds that Tsander "...conducted experiments on the ignition of the air-gasoline mixture in the reaction chamber in the propeller-motor section together with B. S. Stechkin.... The experiments performed at TSAGI were apparently a part of the experimental work of F. A. Tsander related to the creation of his first reaction motor, the OR-1, based on a soldering torch [6, sheets 67-68].

Just what installation is here being discussed? Comparison of certain documents with records in the journal helps us to answer this question. In his statement to the Chief of GIRD, dated 28 November 1932, Tsander calls the installation consisting of the two internal combustions the "OR-0 installation," and reports that this equipment "...will be used in the future for a very large number of different reaction engines" [7, sheet 1].

By comparing the entries in the journal and the recollections of Shukhtirev and Krutikov mentioned above, we can establish the time when experiments were performed on this installation. Shukhtirev mentions 1930. Krutikov affirms that work related to the creation of the OR-1 was performed on it; consequently, before the creation of this motor, before the flame testing of this motor, which as we know occurred on 18 September 1930. In the journal, the first entry in which is dated 5 September 1930, there is no information on the conduct of any experiments using this installation. Mentions of the experimental installation for the study of the process of combustion of a pulsating stream of a fuel mixture, on a motor and compressor are encountered in the journal in January, April and August of 1931; 2 January 1932 and subsequently Tsander refers to the "installation of mot. with pump" as the OR-0 installation. The entries discuss not experiments but the composition of a report concerning work already done (entries of 1931), the repair and modification of the installation. Tsander wrote of his plan for further use of /60
the installation in the report to the Chief of GIRD of 28 November 1932 mentioned above. One of the area of use is mentioned

in the "Program for Times of Operations in the Group of Engineer Tsander, F. A., for 1932." This program was developed in April of 1932 and discusses the work at GIRD. In section "I. OR-1 with Oxygen," we find the subheads: 1) Installation of de Dion Bouton Motor and Brazier Compressor and Receiver on Support; 2) Nozzle for Inlet of Liquid Oxygen; 3) Reconstruction of Support, Scale" [8, sheet 1].

This extract indicates that the first attempts to analyze the entries in the journal has already yielded very interesting results: no information on the experiments of Tsander using the OR-0 installation had previously been encountered in the literature.

A large number of entries relate to the organizational aspect of the work in the area of reaction technology at IAM. On 22 December 1930, two days after being transferred to work at this Institute, Tsander writes: "Preparation for report on work on reaction devices (for technical conference)." On 25 December, the entry reads, "Meeting with Deputy Director of IAM Comrade Belyayevskiy concerning estimates of cost of work on react. eng." On 7 January 1931, Tsander began composing "descriptions of work planned on RE in 1931 at IAM." Then follow several entries on the continuation of this work and a note that on 31 January there was "...the last inspection of the estimates on r. e. and shipping of descriptions of work, estimates and plans to comrade Belyayevskiy, dep. dir."

On 25 February 1931 an entry mentions an event which was very significant in the further work of Fridrikh Arturovich: "Technical conference in the office of comrade Belyayevskiy on the problem of work on r. e. Present: Belyayevskiy, Kravtsov from the Scientific Research Institute, Maslennikov, M. P. Ogloblin, Ye. M. Rozanov. Decided to assign me completely to work on rockets. My report. Previous preparation for tech. conference." After this conference, Fridrikh Arturovich began, using his own words, "to work solely on rockets": whereas in September-December of 1930 he had spent an average of 40-50 hours per month on this work, after this conference -- 155-160 hours.

In later entries we find information on the selection of personnel for work on reaction equipment, the development of a program of operations. The "program of operations on reaction engines at the first IAM BR Laboratory and "R" Laboratory of IAM for 1932" has been preserved [8]. This document of the Tsander collection has not been dated, but can be dated by referring to the journal: on 25 October 1931, Tsander wrote that he "...revised and turned in program of operations for 32, form 1 and 2." We must note the positions of those who wrote the document: the former was the Laboratory Chief, the latter the "Reaction Engines Team Chief." This document, and analysis of the entries in the journal, confirm once more that work on

reaction equipment was conducted in a planned manner at IAM as well as the Gas Dynamic Laboratory and the General Theoretical Section of TSAGI, the organization was formalized and supplied with materials.

The journal contains rather extensive information concerning the range of scientific interests of Tsander. Suffice it to say that in two years he made 26 entries concerning books and articles he read, 15 entries concerning reviews and references to inventions. He carefully followed everything new which appeared in his chosen area of science and technology. We read an entry concerning the study of the works of K. E. Tsiolkovskiy, a number of entries on the works of G. Oberth. On 16 July 1931, Tsander wrote, "Read description of invention of Petropavlovskiy 'Reaction Engine' and wrote a review of it." On 8-10 December 1931 he wrote reviews concerning the inventions of V. P. Glushko /61
"A Reaction Flight Vehicle" and "A Fuel Tank for a Reaction Engine."

Many famous scientists and specialists were familiar with the works of Tsander, including the experiments on the OR-1. On 29 November 1931, the 39th experimental run of the OR-1 was witnessed by N. A. Rynin. On 17 May 1931, Tsander demonstrated by OR-1 to V. P. Vetchinkin, on 21 January 1932, the 43rd experiment with the OR-1 was witnessed by A. V. Krasnikov, on 4 March 1932 Tsander told V. P. Glushko of his work.

The journal helps to give us an idea of the working style of Fridrikh Arturovich. We should note first of all that he was not an "individual inventor." This is easy to see, for example, in the development of the OR-2. The first mention of the beginning of specific work on this engine is probably the entry of 10 September 1931, "...typed review of types of r. e. now used for installation on aeroplane." On 15 September -- an entry concerning his resolve "...one day in five to work 'on react. eng. f/aeroplane.'" (This engine is first referred to as the OR-2 in the journal on 19 October 1931.) On 20 September 1931, Tsander met with TSAGI engineer Levitskiy "...concerning the rocket aeroplane and its engine." Tsander maintained close connections with Levitskiy in the future as well, exchanging with him opinions on many subjects -- the design of the OR-2, the general form of the working drawings, etc.; the journal contains 12 entries concerning meetings and cooperative work with Levitskiy. On 1 October 1931, Tsander himself "...concerning the installation of the RF on an aeroplane" with Yu. A. Pobedonostsev, with whom he constantly maintained contact in the future as well.

On 5 October 1931 we find the first entry concerning his joint work with S. P. Korolev -- a trip to the Osoaviakhim Airfield and inspection of a glider. Apparently, this was not their first meeting. In any case, V. A. Andreyev in his recollections concerning a conversation with Korolev and Tsander in October of 1931 writes, "...judging from the conversation and

the businesslike relationship which I observed at that time, it could be concluded that Sergey Pavlovich and Fridrikh Arturovich were quite well acquainted before this conversation" [9, sheet 12, ob.]. Entries on the joint work with Korolev are encountered in the journal right up to the summer of 1932.

Beginning in January of 1932, Tsander established close and businesslike relationships with A. I. Polyarnyy. Many entries indicating this are encountered up to July of 1932.

We should mention particularly here M. P. Ogloblin, the Chief of Laboratory I of IAM. Judging from the entries in the journal, as well as certain other documents, he was vitally interested in the problems of reaction technology. In a report on the session of BIRD of 17 July 1931, he is mentioned as Deputy Chairman of the Bureau [8]. In Tsander's journal, the name Ogloblin is mentioned beginning 27 December 1930 and continuing through 21 February 1932, a total of 18 times. He was very helpful to Tsander in solving organizational problems related to his work on reaction equipment.

We could note many more names. In all, Tsander's journal mentions the names of 106 persons, involved to a greater or lesser extent in work in the area of reaction equipment. In many cases, study of the information related to people whose names are mentioned in the journal can yield very interesting results.

Tsander's working journal is a valuable historical document. The labor involved in preparing it for publication would be fully justified. If well prepared for publication, and supplied /62
with commentary it will doubtless attract the attention of specialist historians and will be of interest for a broad range of people interested in the history of Soviet rocket technology.

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4. Archives of Academy of Sciences USSR, Folio 573, List I, File 265.

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6. Archives of Academy of Sciences USSR, Folio 4, List 14, File 224.

7. Archives of Academy of Sciences USSR, Folio 573, List I, File 53.

8. Archives of Academy of Sciences USSR, Folio 573, List I, File 265.

9. Archives of Academy of Sciences USSR, Folio 4, List 14, File 224.

[1]File 260, entries from 5 September 1930 through 16 December 1930; File 266, entries from 20 December 1930 through 5 August 1932. Materials of folio 573, inventory I are presently being processed, therefore we cannot give the sheet numbers in references to Tsander's working journal and certain other documents of this inventory and folio.

SCIENTIFIC AND TECHNICAL ANALYSIS OF THE DECIPHERED MANUSCRIPTS OF F. A. TSANDER

Yu. V. Klychnikov

1972 marked the 85th anniversary of the day of birth of Fridrikh Arturovich Tsander -- one of the founders of rocket technology and interplanetary flights, a great Soviet scientist, a pioneer of Soviet rocket building.

In the first stage of development of rocket technology and astronautics, researchers have many unsolved problems before them, particularly in the areas of astronomy, ballistics, rocket building, motor building, chemistry, metallurgy, mechanics, physiology, etc. If we evaluate the work of the founders of rocket technology, we can note one important peculiarity, namely: they almost all worked not on one, but on a number of problems. Tsander was also involved in practically all of the problems listed above.

F. A. Tsander's book Problema Poleta pri Pomoshchi Reaktivnykh Apparatov [The Problem of Flight by Means of Reaction Apparatus], in which he summarized the results of his many years of investigation in the area of rocket technology, was published in 1932. He then began preparing for publication several more books on rocket technology, but his early death interrupted this work. The conspectus of chapters, as well as several manuscripts for Tsander's book which he planned to publish under the title "Flights to Other Planets: The First Step into Limitless Space (Theory of Interplanetary Voyages)" have been preserved to this day. Tsander began working to prepare this manuscript for printing in 1926. Also preserved is the program for his book, also unpublished, "Design of Reaction Engines and their Combination with Engines of Other Types." In the book "Flights to Other Planets," Tsander planned to include sections dedicated to various problems of rocket technology, particularly the following: calculation of flight trajectories for interplanetary spacecraft, design and calculation of interplanetary spaceship-aeroplanes, apparatus transforming solar rays into low-velocity cathode rays, flights by means of the pressure of cathode rays, etc. /63

However, the full collected works of F. A. Tsander have never been published, since a significant portion of his manuscript has not yet been deciphered or studied. The difficulty in performing this task lies in the fact that Tsander, in order to save time, wrote a portion of his work and calculations in shorthand. Deciphering of these shorthand records is complicated still more by the fact that even on a single page, he wrote in more than one language (in Russian and German). Difficulties arise in deciphering the manuscripts also due to the fact that Tsander frequently referred to entries and calculations made in

other notebooks, some of which have not yet been found. Tsander used a shorthand system which is no longer in use, the Gabbelsberger stenographic system. This shorthand system he apparently studied in the Higher Technical School in Danzig, which he attended from 1905 through 1907. Shorthand was one of the disciplines studied at the Higher Technical School in Danzig. Although the diploma received by Tsander upon completion of this school does not indicate the system of shorthand taught there, if we consider the fact that the most widespread system of shorthand used at the time in Germany was the Gabbelsberger system, we can assume that Tsander also studied this system of shorthand. One reason for this might have been the fact that there was at that time no national Russian system of shorthand.

The most popular system of shorthand in Russia at the end of the 19th and early 20th centuries was the Gabbelsberger system. This system of shorthand was widely modified to allow its use for the Russian language. Each author introduced his own characters for the Russian letters; many changed the significance of certain German letters for the same Russian letters, each author gave his own abbreviations for prefixes, endings, etc. As a result of this, in Russia there was not just one Gabbelsberger system, but more like 10. This in turn additionally complicates the deciphering of the manuscripts of Tsander written in the Russian Gabbelsberger shorthand system.

Usually, shorthand records are used during presentations, speeches, lectures, etc. Why did Tsander use shorthand for his journal entries and technical calculations? It is difficult to answer this question definitely. Possibly to save time? However, these records must be later deciphered and processed and, consequently, there is no total time saved. Based on a detailed study of the shorthand records and the works published by Tsander himself, we can assume that he used shorthand in order to save time during writing, since he did not, apparently, plan to publish all of his writings and was primarily involved in research work. This is also indicated by the large number of draft entries made in shorthand.

Tsander mentions the fact that he plans to make his entries in shorthand using the German Gabbelsberger system in his work "Space (Ether) Ships for Journeys Between Stars. Movement in World Space. Flight in the Air and Space" in his entry of 19 October 1908 (old date). In particular, the first shorthand entries involving technical calculations of Tsander were discovered by the author in this work beginning on 9 March 1909. /64

The shorthand entries of Tsander cover the period from 1909 through 1932. In this time, both the nature of the entries and the shorthand transcription underwent a number of changes. In manuscripts dated 1909-1912, Tsander wrote mostly in German using the Gabbelsberger shorthand system. In later years (1912-1917), the same shorthand system was used, but in

several places shorthand characters are encountered which have been altered in comparison with the "classical" system. This apparently resulted from the peculiarities of emphasis and style of Tsander. For this reason, in order to decipher these entries, the author was forced to compose a dictionary of the meanings of the new characters and abbreviations. It should also be noted that until the end of 1917, Tsander dated his entries according to the old calendar.

Beginning in 1917, entries begin to appear in Tsander's manuscripts which are written in shorthand but in Russian rather than in German. This is apparently explained by the fact that he was forced increasingly to speak in Russian, since in 1915 he traveled to Moscow in connection with the evacuation of "Provodnik" Plant, Tsander's place of employment, from Riga. However, these entries are not made in the Russian Gabbelsberger shorthand system, but in a somewhat unusual system developed by Tsander himself: Russian letters which are similar in sound to German letters are written in the German shorthand system.

Furthermore, the formulas, coefficients, dimensions and symbols used by Tsander in his calculations are not presently in use; therefore, after deciphering the text, the author has been forced to perform the cumbersome work of technical editing of the text.

The archives of the Academy of Sciences USSR contain significant numbers of documents describing the life and activity of F. A. Tsander. These documents make up a separate file, including some 700 storage units. The first collection of materials in the Tsander archive began at GIRD (the Group for Investigation of Reaction Motion) in 1933, soon after the death of the scientist, initially on the initiative of the GIRD workers, then by resolution of the Central Council of Osoaviakhim of 6 May 1933, after which the collected works of Tsander began to be prepared for printing.

The author began working on the Tsander archive in 1969, for which purpose he had to make a special study of the Gabbelsberger shorthand system in both German and Russian.

Due to the large volume of shorthand manuscripts (some 7000 pages), it was impossible to decipher all of the works of Tsander in sequence in a short period of time.

Furthermore, the archives of the Academy of Sciences USSR contain many works of Tsander dedicated to various technical and secondary problems not relating to rocket technology. It should be added that not all of Tsander's manuscripts are contained in the archives, creating certain difficulties in the study of the scientific heritage of Tsander, since the beginning and continuation of various works of Tsander have not yet been

found by the author. Considering the difficulty of deciphering Tsander's manuscripts, as well as the fact that the author deciphers only technical manuscripts related primarily to rocket, aviation and space technology, the following sequence of operations has been used:

1) Preliminary inspection of shorthand manuscripts in order to determine the nature of the entries; /65

2) Selection of manuscripts dedicated to problems of rocket, aviation and space technology, without analysis of their scientific and technical value;

3) More detailed inspection of the manuscripts on rocket, aviation and space technology in order to determine their content;

4) Detailed deciphering or abstracting of the most interesting works.

In some individual cases, the selection of manuscripts for detailed inspection and deciphering has been performed with a purpose in mind. In particular, it has never been established just what sort of report Tsander made at the Governor's Conference of Inventors held on 29 December 1921 through 2 January 1922 in Moscow, since at the present time we know only the program of the conference, not the authors of the reports.

It has also never been established just how V. I. Lenin promised to support F. A. Tsander, as Tsander mentions in his autobiography. An attempt has been made to find a report of this remarkable fact in the journals of Tsander, but a preliminary inspection of the shorthand journal entries of Tsander between December 1921 and January of 1922 yielded no positive result.

The author has inspected all of the manuscripts of Tsander both those in shorthand, as well as those written in German and in Russian.

The entries in German and Russian were inspected not only because they are of definite scientific and technical interest, but also because Tsander, as he returned to earlier manuscripts, frequently made shorthand notes on them. These shorthand notes are also of great interest for historians for an estimation of the stages of development, improvement and realization of various technical and scientific ideas and suggestions of Tsander. The author has prepared a brief annotation of all of the shorthand manuscriptsof Tsander, and has also fully deciphered and translated from German the works of Tsander "Space (Ether) Ships for Voyages to the Stars. Movement in World Space" (see Iz Istorii Yestestvoznaniya i Tekhniki Pribaltiki [From the History of Natural Science and Technology of the Baltic States], Vol. 4, 1972).

This work of F. A. Tsander can be considered his first scientific research dedicated to interplanetary voyages. Tsander hardly intended for this work to be published. As we can see from the text, these are working, almost journal entries concerning calculations which Tsander made "for himself," apparently in order to estimate the nature and peculiarities of the technical difficulties involved in interplanetary flights. Still, this work does include a number of ideas and suggestions made by Tsander which have been further developed and used in modern technology. We must not forget that during the time this work was written, Tsander was still a student at Riga Polytechnical Institute. In the literature of those years there were practically no engineering designs for spaceships. Therefore, many calculations seem rather simple from today's point of view. However, in this work Tsander used as his basis the achievements of physics, astronomy, the strengths of materials, zoology and other sciences known at the time.

Using these achievements, Tsander moves further and sets forth a number of very interesting ideas on the problems of space flights. In particular, in this work he calculates the conditions of flight to other planets with the minimum expenditure of work in the shortest period of time, analyzes conditions of crew life support during a space flight, makes suggestions for the utilization of elements of the structure of the flight vehicle as fuel, suggests that the magnetic field of the Earth be used to produce lift and discusses a number of other actual and hypothetical problems. /66

The work was begun by F. A. Tsander in 1908 and completed in 1912. For a long time, it was unknown to investigators of the scientific creativity of Tsander, since it was stored in the personal archives of the scientist and was written in shorthand in German using the Gabbelsberger system. Only a small portion (the beginning) of this work was written in German with shorthand notes, comments and additions [1, pp. 3-36].

It is interesting to note that Tsander later returned repeatedly to this work, since the text of the manuscript includes comments and additions dated from 1918 through 1923.

In F. A. Tsander's book "The Problem of Flight by Means of Reaction Apparatus," there is a reference to the fact that in his manuscript of 11 March 1909 he had already expressed the idea of the desirability to use the entire mass of the rocket as fuel [2, p. 71]. For a long time, researchers attempted to find this manuscript, but without success. In deciphering the manuscript of "Spaceships for Travel to the Stars. Movement in World Space," it was found that in this work, in the entry of 11 March (old style of dating), Tsander actually did write that the maximum flying altitude could be achieved by using elements of the structure of the rocket no longer needed for further flight as fuel.

C.2

Subsequently, in 1932, in the book "The Problem of Flight by Means of Reaction Apparatus," he wrote, "In many cases, only a small number of the parts of the structure of the flight vehicle will be required as fuel, not all that are available. As the designs are improved, the number of parts burned will decrease, but until the problem of 'mastering' interplanetary space is solved, the aeroplane alone will be of very insignificant value."

Actually, up to the present time, as the process of "mastery" of interplanetary space continues, all of the structures of flight vehicles (space vehicles), with the exception of a small number of certain parts of the last stages of the booster rocket, are used but once, and the problem of the cost of a launch is not the determining factor. Up to the present time, no method has yet been found for combustion and utilization as fuel of the parts of the structure of a flight vehicle. Thanks to the progress in the development of designs of rockets and rocket engines, as well as rocket fuels, the weight of the structure of a rocket at the present time amounts to a small portion of the launch weight of the rocket.

In particular, the relative weight of structures of rockets is as follows: the Scout of 1960 -- 23.5%; the Atlas-Agena D of 1961 -- 21.6%; the Atlas Sentor of 1963 -- 21.2%; the Saturn-1 of 1964 -- 11%; the Saturn-1B of 1966 -- 11.2%; the Saturn-5 of 1967 -- 7%. The relative weight of the structure of space vehicles has a tendency to decrease and, apparently, the idea of burning and using as fuel the elements of the structure of the structure of the rocket, due to the technical difficulties involved, will not be realized. It is simpler to use the unneeded portions of the structure of the rocket again, by saving them by various methods, particularly by following the suggestion of Tsander to allow them to glide back to Earth. /67
It should be noted that even what seems to be F. A. Tsander's most fantastic ideas at first glance have not been either rejected or accepted a priori. An example of this is the idea of utilization of a cable for regular voyages between the Earth and the moon, with the ends of the cable attached to these two bodies. In 1910, Tsander estimated the possibility of technical achievement of this idea. He calculated the position of the point of equilibrium between the Earth and the moon considering their geometric dimensions and the acceleration of the forces of gravity of the two bodies. Assuming the ratio of mass of the Earth and the moon to be equal to 81 and the distance from the Earth to the moon to be 384,420 km, Tsander estimated the point of equilibrium as 345,978 km from the Earth and 38,422 km from the moon. At the end of his calculation, Tsander refined these distances considering the angular velocity of rotation of the moon relative to the Earth, $2.66 \cdot 10^{-6}$ 1/sec. These distances were then calculated as 327,000 and 53,800 km.

Based on the forces arising in the cable due to the forces of gravity of the Earth and the moon and the strength characteristics of steel cable, Tsander concluded a formula for determination of the thickness of the cable at any distance from the point of equilibrium of the cable with assigned thicknesses at the surface of the Earth and the moon. For example, with a cross-sectional area of the cable at the surface of the moon of 1 mm^2, the cross-sectional area of the cable at the point of equilibrium would be 1,000 m^2 (diameter 36 m).

Since the distance between the Earth and the moon changes continuously between 363,310 and 405,520 km and the moon moves around the Earth, Tsander suggested that a tall tower be constructed on the moon, to which the end of the cable would be attached. The position of the center of equilibrium of the cable could then be maintained constant by rotating a drum installed on this tower, to wind and unwind the cable or by a "tender" type mechanism installed at the equilibrium point. Doubtless, this suggestion of Tsander is practically impossible, but we must note its originality, as well as the fact that he did solve the problem technically correctly. We should add to this that in modern plans for the creation of interplanetary spaceships rotating around a common center of mass in order to create an artificial force of gravity, regular cable systems are frequently used.

Further in this work, F. A. Tsander analyzes the flying height of a spacecraft with variations in the specific weight of the engine and work performed: he draws certain conclusions as to the conditions under which the reaction of the jet of gas exhausting from the nozzle will be at its maximum (in particular, he draws the conclusion, correct from today's point of view, that the reaction of the jet of gas depends on the pressure in the vessel and the shape of the nozzle).

In his work "Space (Ether) Ships for Voyages to the Stars. Movement in World Space" of 13 March 1909, Tsander writes, "The fuel for the engine to be used to accelerate the flight vehicle can include, in addition to gas, also water or some other substance." In itself, the idea of using hot water under pressure in the saturated state as a working fluid for a rocket had been stated long ago.

As an example, as we know, the first prototype reaction engine was the sphere of Hero of Alexandria, constructed in 120 b.c. Only much later, in 1937-1939, was a plan developed in Germany for the use of a water rocket as the drive system for a trolley for experiments in the area of sonic velocity. The problem of the water rocket was studied in 1940-1941 also by the Heinkel Company [3, p. 3]. As we know, at the present time such devices are used in aviation and rocket technology;

in particular, aircraft takeoff from aircraft carriers using steam catapults for acceleration [4].

The water rocket as a means for vertical ascent can be used in high altitude research rockets [3, p. 5]. Due to the low specific thrust of the working fluid (60 sec), only multistage rockets are promising. These shortcomings are compensated for by the simplicity of design, reliability and exceptionally low cost of such a rocket [3, p. 12]. /68

In this same work of 20 March 1909, in analyzing a flight vehicle with an air-breathing engine, Tsander suggested that the resulting velocity of the flight vehicle be determined as the difference between the exhaust velocity of the gas from the nozzle of the engine and the velocity of the incoming air stream ($v - v_1$). Subsequently, as we know, B. S. Stechkin in his work "The Theory of Air-Breathing Reaction Engines," (1929) [5, p. 99], in determining the thrust of his engine, used the expression $R = m(v - v_0)$, where m is the mass of gas passing through the engine; $v - v_0$ is the difference in exhaust velocity of the gas at the nozzle of the engine and the velocity of the incoming stream. Comparing the expression enclosed in parentheses with the expression for determination of the resultant velocity suggested by Tsander, we see that even in 1909 Tsander had basically correctly evaluated the initial components of the characteristics of jet engines.

In an entry of 6 June 1910, Tsander suggested the use of the Lorentz thrust force to move a spacecraft within the limits of the Earth's magnetic field. His estimates showed that this method of production of an interacting force can be used in the following cases: for adjustment of the orbit of satellites; to measure the trajectory during the descent of an apparatus reentering the atmosphere at escape velocity, and also for the orientation of a flight vehicle with controllable electrostatic dipole moment [6, p. 242]. In his subsequent works, Tsander studies this method of movement of spaceships in detail.

In 1912, Tsander analyzes the flying altitude of a flight vehicle of constant and variable mass and shows that if the mass of the vehicle decreases during flight (consumption of fuel per second constant), the flying altitude is increased significantly. He then demonstrated that at the moment of launch, the required fuel consumption should be maximal, decreasing asymptotically with increasing altitude.

In another work of Tsander, notebook IV (file No. 73; begun 19 January 1916, completed 30 June 1931), under the heading "The Use of Plants for the Production of Energy for a Limited Period of Time," the entries are made in shorthand. In this notebook, Tsander wrote, "During flight around the Earth

and to other planets, the crew of the spacecraft must be fed and provided with energy by the spacecraft. For this purpose, Tsander suggested that various plants be grown on board the spacecraft, particularly radishes, lettuce, peas and others, using the hulls of the seeds as fertilizer and sand or, for example, small glass beads as soil, as well as the water and wastes of the vital activity of the spacecraft crew. Water, carbon and other substances, Tsander suggested, should be obtained by processing of wastes, utilizing a regenerative cycle. This is followed by calculations of the quantities of oxygen, carbon and other substances necessary for the life of the members of the crew of the spacecraft, and recording of the observations of the growth of various plant seeds.

Subsequently, Tsander continued his experiments on the growth of plants in a greenhouse, and his work on the use of the regenerative cycle of reprocessing the wastes of human vital activity were further developed in modern space biology (medicine). /69

All of Tsander's manuscripts can be classified as follows.

1. Technical suggestions and calculations to form the basis of his own scientific ideas.

2. Calculations to evaluate the suggestions of other authors and various technical ideas.

3. Production calculations, which he performed during his employment at "Motor" and "Provodnik" Plants, as well as IAM.

4. His personal correspondence.

5. His journal entries.

Of the ideas and suggestions found in the manuscripts of Tsander by the author, in addition to the subjects we have covered, the most interesting are as follows.

Combined rocket-airplane system. According to this system, a rocket motor is located in the tail portion of the fuselage of an airplane, and begins to operate at high altitude over the surface of the Earth. A piston engine located in the fuselage in the plane of the wings is used to take off and climb to altitude. A transmission located in the wing and connected to this piston engine rotates two shafts, at the ends of which are four propellers. This plan was developed by Tsander in 1921 [7]. In addition to certain shortcomings of this plan, related to the presence of the transmission, we can note a number of advantages. In particular, the location of the piston engine in the fuselage of the aircraft allows the drag

to be reduced in comparison to the plan of installation of the engines on the wings, considering the comparatively large transverse area of piston engines.

In spite of the fact that Tsander's plan was never practically realized, we must note that Tsander was working at the technical level of his time in attempting to solve the practical problems of flight of rocket planes within the Earth's atmosphere.

In later years, the idea of creation of combined vehicles (with both piston and rocket engines), suggested by Tsander, was repeatedly set forth in various countries and even realized, though not for space travel purposes. We need but recall the American Bell X-1 liquid fueled experimental aircraft, which was suspended from a B-29 with piston engines, or the kamikazi rocket fighters used by the Japanese during the second World War [13, p. 88, 110]. During the post-War years, the development of the idea of combined space vehicles continued utilizing jet engines.

Airplane with rocket engine. In his manuscript of 7 March 1920, two plans of winged rockets are drawn. The more interesting is a plan of a rocket with "duck" wings [8, sheet 129].

The idea of the expediency of using an airplane in the upper layers of the atmosphere, and also for gliding descent to planets which have an atmosphere, was stated by Tsander in print for the first time in 1924 [9, pp. 15-16].

As concerns the two plans of winged rockets suggested by Tsander, in this case the documentary materials confirm that Tsander began working on the idea of the winged rocket, set forth in 1924, somewhat earlier.

Rockets with fuel tanks located outside the body of the rocket. In Tsander's manuscript of 8 March 1925 [10], there are plans for rockets with tanks of fuel (hydrogen or gasoline) and oxidizer (oxygen) located on the sides of the fuselage on pylons. /70
In one plan we see winged fuel tanks located around the body of the rocket. These tanks have a streamlined shape. At the present time, many nations have developed various plans for single-stage air-space vehicles (the "Rombus" project in the USA, the "Beta" project in West Germany), calling for the installation of fuel and oxidizer tanks around the body of the rocket. This placement of tanks allows the design of the booster rocket to be simplified (decreases the dimensions of the rocket; makes it possible comparatively simply to separate and jettison these tanks after the fuel is expended; a single motor installation is sufficient for the entire flight; if the tanks are of the required aerodynamic shape, they can be used to generate additional lift; problems of servicing on the surface are simplified,

etc.). A plan for a rocket with fuel tanks located spirally around its body, published by Tsander in his book [2, p. 51], is a further development of the plans for rockets with fuel tanks located on pylons on the sides of the fuselage found in his manuscripts.

As further development of rocket-space technology demonstrated, the plans produced by Tsander in 1925 are presently being realized. Thus, we can conclude that this idea of Tsander was further developed in current-day rocket technology.

Combined engine. In Tsander's manuscript of 6 January 1922 [11, sheet 78], there is a diagram and description of the operation of a combined power plant, consisting of a piston engine with three cylinders, one of which is not used for ignition of the mixture, but rather for compression of a mixture which then travels through a special pipe to a combustion chamber. The combustion products from this chamber are exhausted through a supersonic nozzle. This system is a further development of the system of a piston engine with exhaust of the combustion products through a supersonic nozzle suggested in 1908 by Lorin [12, p. 464].

The plan suggested by Tsander for a combined power plant allows the thermodynamic cycle of the process to be altered, increasing the thermal efficiency of the engine. It is to Tsander's credit also that this plan for a motor installation allowed the technology of the piston engine to be used to study and investigate ignition, combustion and other processes in liquid-fueled rocket engines, which were new at the time.

Subsequently, this plan of Tsander for a power plant was used in creating the OR-0 engine, which was used for experimental investigations.

As we know, subsequently in Italy Campini planned and built a similar motor-compressor installation in the early 1940's [13, p. 43]. One shortcoming of this plan was the lack of a gas turbine, the function of which was performed by a piston engine with significantly lower efficiency. Nevertheless, by the use of precombustion of the fuel, the maximum velocity of the N-1 aircraft, flying from Milan to Rome in 1941, was 375 km/hr at an altitude of about 3 km [13, pp. 43, 72].

Another interesting idea of Tsander is his suggestion to increase the flying efficiency of a rocket engine by ejecting the surrounding atmosphere [9, p. 16].

We must note that in this case Tsander was not suggesting the use of the atmosphere of the air in the process of combustion, but rather considered that the entire mass of the air, as

an inert gas, would simply increase the mass flow rate of the exhaust gases and decrease their exhaust velocity. Since in those days work on the creation of LRE was in the stage of experimental development of individual structural elements, Tsander was not yet able to realize yet another advantage of air ejection, namely the fact that the ejector nozzles installed on the LRE nozzles, can lead to a significant increase in the thermal efficiency of the engine, since the air drawn in is heated by the jet as a result of further combustion of the fuel components always present around the periphery of the exhaust jet of an LRE. According to modern estimates, air forcing of rocket engines can increase the economy of the power plant over the initial portions of the lift trajectory and increase the payload weight by 20%. /71

It was considered until recently that the first suggestion for air ejection in rocket engines was made by Tsander in 1924. However, detailed study of the shorthand manuscripts of Tsander has allowed the author to find a diagram and brief description of a rocket engine made so that the walls of the supersonic portion of the nozzle consist of a group of cylindrical elements for ejection of the surrounding atmospheric air in a manuscript from 1921. This design of the nozzle also allows its hot walls to be cooled by the ejection of the surrounding air.

Subsequently, Tsander, using the schematic diagram of the Melo nozzle, made a number of interesting suggestions. This is indicated by the plans discovered by the author in the shorthand manuscripts of Tsander of 1928 [14]. In one (18 August 1928), Tsander slightly altered the design of the nozzles and suggested that magnesium and air be used as the fuel and oxidizer.

However, another plan (24 August 1928), in addition to its originality, has a number of shortcomings, In particular, in this plan Tsander suggested that the combustion chamber of an LRE be used to burn a gas consisting of air and the combustion products drawn away from the periphery of an exhaust nozzle. The gas extracted from the periphery at the output of the nozzle has comparatively low static pressure. Without additional compression using a special compressor, this gas could not be used as an oxidizer in a rocket engine. This plan has no advantages over the usual plan of compression and feeding of the air (as in the air collector of a jet engine). This plan is very complex and cumbersome. It is simpler to decelerate and compress the incoming unperturbed air stream in an air collector than to decelerate, rotate and compress a stream of gas consisting not of pure air, but of air mixed with the combustion products of the LRE and preliminarily accelerated in a supersonic nozzle, since this increases the hydraulic drag and requires special cooling of the stream heated by the jet of gas leaving the combustion chamber of the LRE.

A logical development of the rocket suqgested by Tsander in 1924, "adapted for flying in the air," is a plan for a rocket-turbine engine without mixing of streams discovered by the author in the Archives of the Academy of Sciences USSR among the unprocessed and undeciphered manuscripts of Tsander [15]. This plan was dated by Tsander 12 April 1932. According to this plan, a two-stage turbine is installed in the output portion of the nozzle of a reaction engine, so that a propeller is installed on the periphery of the hub of the second stage. The thrust of this engine consists of two components: the thrust created by the reaction jet, and the thrust produced by the propeller. The creation of thrust due to the reaction of a gas jet is more effective at higher flight velocities (M > 1), the thrust produced by the propeller is more effective at low and moderate velocities. Thus, this power plant allows the flight of a vehicle over a practically unlimited range of speeds and altitudes. At that time, there was still no classification of combined rocket engines, and therefore Tsander called his plan an air-reaction engine combined with a gas turbine. This plan was somewhat more complex than the "rocket adapted for flight in the air," but more effective for comparatively low flight speeds. The presence in this plan of the propeller somewhat limits the range of altitudes and velocities of flight due to the low effectiveness of the propeller at high altitudes and high flight velocities. /72

Analyzing this plan, we can see that it has a number of elements in common with the jet engine with individual cycles, improved cycles and also with the engine in which the products of combustion are mixed with the air without shock [2, pp. 31, 36, 37]. For example, all of these plans include a forward and inverse cone, ejection of the air of the atmosphere, etc. The main difference in the plan of the air reaction engine and its combination with the gas turbine from all other plans is the presence in the output portion of the nozzle of a two-stage turbine with a propeller installed on the periphery of the crown of the second stage. As was noted earlier, the use of the propeller allows economical flight of the vehicle at low altitudes and flight speeds. Based on what we have said, it can be concluded that this plan is a further development of his plans for jet engines with separate and improved cycles.

The plan for the rocket-turbine engine (RTE) suggested by Tsander has individual elements found in a modern turbofan engine with rear placement of the fan, namely the structural plan of location of the three-fan turbine on the outer rim. True, turbofan engines with forward placement of the fan are now used, since this plan decreases the cross section of the engine in comparison with rear placement of the fan.

We should also note one additional peculiarity of the development of the creative thought of Tsander. Whereas earlier, in 1921, Tsander suggested that a separate power plant consisting of piston and rocket engines be installed on a flight vehicle,

in the case of the RTE we actually have the entire power plant combined into one unit, which has significant advantages over separate units (including the absence of the cumbersome and complex piston engine).

It should be noted that in 1933-34, K. E. Tsiolkovskiy suggested a plan for a steam-gas turbine engine [16, pp. 401-409], in which there is also a turbine at the outlet of the supersonic nozzle, rotated by the exhaust gases. The shortcoming of this plan in comparison to the RTE of Tsander is the unsuccessful design of the drive of the propeller by the turbine, namely in that this drive requires a transmission located in the stream of hot gases leaving the nozzle. Tsander solved this problem structurally correctly, which is confirmed, as we have noted, in the jet technology of today. We should note that Tsiolkovskiy suggested his steam-gas turbine engine significantly later than Tsander drew up the plans for his RTE. Unfortunately, Tsander's plan was not published, but it is possible that Tsander described this plan in his lectures and reports. However, additional research is required to clarify this question. /73

The plan suggested by Tsander was significantly ahead of its time. RTE began to be developed abroad significantly later. In Germany, RTE began to be studied only during the second World War. And it is even later than this, in the 1950's, that scientific research work on RTE was conducted in England and the USA. As is noted in the foreign literature, RTE must be looked upon as the probable power plant for aircraft and the first stage of booster rockets. In another of his works, Tsander performed detailed engineering design of a machine for the production of liquid air. The operation of this machine was based on the idea of using the significant drop in temperature occurring when air under pressure is expanded. As a result of his calculations, Tsander determined the quantity of energy necessary for the production of liquid oxygen and nitrogen, considering thermal and thermodynamic losses.

In 1921, Tsander performed calculations using the special theory of relativity in order to determine the longitudinal mass of a body on the Earth as it moves through space.

The results of interpretation of the shorthand manuscripts of F. A. Tsander performed by the author are presented in more detail in the works of the First, Second and Third Readings Dedicated to Development of the Scientific Heritage and Ideas of F. A. Tsander [17, pp. 129-137; 18, pp. 81-87; 19, pp. 68-73].

It should be noted that analysis of the shorthand manuscripts of Tsander shows that many published suggestions and ideas of Tsander were developed significantly later. In studying these suggestions, we can trace the process of their development

in the scientific creativity of Tsander.

In the future, we must decode and translate from the German many more of Tsander's works on the problems of interplanetary flight.

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THE F. A. TSANDER COLLECTION IN THE ARCHIVES OF THE ACADEMY OF SCIENCES USSR

L. G. Samokhvalova

The history of rocket-space technology attracts ever greater attention year after year. Therefore, it is natural that historical researchers, writers and journalists are interested in the documentary materials on the history of the institutions, societies and organizations working in the area of rocket technology, in materials on the life and activity of the scientists, engineers and designers whose labor created and developed this new area of science and technology.

The Archives of the Academy of Sciences USSR represent the country's largest scientific archives, concentrating a complex of documents deposited as a result of the scientific and scientific-organizational activity of the Academy of Sciences USSR and its institutions, as well as the personal collections of outstanding domestic scientists over the almost 250 years of existence of the Academy of Sciences. All of this makes the Archives a valuable documentary base for the history of science.

The location and accumulation of documentary materials is not a goal in itself for historian-archivists. At the Archives, great work is done on the processing and scientific investigation of the collection, and traditional forms of their utilization are practiced: lending of files for work in the reading rooms, exchange of reports with scientific research institutions of the same type, exchange of information by lending files for temporary use, response to thematic requests, organization of exhibits, etc.

As a result of many years of work in the Archives of the Academy of Sciences USSR, a significant number of documents has been accumulated on the life and activity of Fridrikh Arturovich Tsander. These documents make up a separate collection including some 700 storage units. The purpose of the present report is an attempt to provide a brief archeographic description of this collection. Such a description will obviously be of interest for participants in the Tsander Readings. However, we must note that it is impossible to describe fully the entire composition and content of the F. A. Tsander collection in one brief report. /75
Therefore, we will turn our attention to certain dates and groups of documents and at times will be able only to list them.

The first attempt to gather the fullest possible Tsander collection was undertaken at GIRD in 1933, soon after the death of the scientist. This collection was then stored and worked on in

the Reaction Scientific Research Institute (RNII) and organizations which developed on its basis. The Archives of the Academy of Sciences USSR (then the Moscow Division) received the personal archives of F. A. Tsander on 2 August 1940. Archive processing of the personal collection of F. A. Tsander assigned the number 573 by the Archives of the Academy of Sciences USSR, was completed in November of 1949, and an inventory of 273 storage units was composed.

In February of 1957, the F. A. Tsander collection was shifted to the N. Ye. Zhukovskiy Scientific Memorial Museum, and only in June of 1966 was it returned to the Archives of the Academy of Sciences USSR. Significant work had to be done on the collection. First processed some 30 years earlier, it did not meet modern rules and requirements for the scientific and technical processing of documentary materials in the collections of scientists.

Over the past 4 years, the collection has been significantly supplemented by new documents and materials. A vote of thanks is due to Astra Fridrikhovna Tsander who in August of 1968 transferred the Tsander family collection to the Archives of the Academy of Sciences USSR.

The Archives of the Academy of Sciences USSR and the Institute of the History of Natural Science and Technology, Academy of Sciences USSR, have adopted a resolution, under which the materials of F. A. Tsander are being processed and scientifically described, and the scientist's shorthand records are being deciphered. A Commission for Development of the Scientific Heritage of F. A. Tsander, headed by Academician V. P. Mishin, has been set up in the Department of Mechanics and Control Processes, Academy of Sciences USSR, and is now in operation. The Commission includes famous Soviet scientists, many of whom worked together with Tsander.

The F. A. Tsander collection covers the period from 1887 through 1933 and consists of 5 groups of materials, corresponding to the five files in the collection: scientific and popular scientific works; biographical material; material on his activity; correspondence; and illustrative materials.

The first group of materials includes some 500 items dated from 1904 through 1933. Almost all of these materials, with a few exceptions, are written in Tsander's hand or are authorized typescripts.

Of greatest interest are the scientific works and scientific-popular works of Tsander, including the manuscripts for his books and articles, lectures and reports, calculations, drawings, plans, graphs, descriptions of designs and other similar materials in Russian and German. These include most of his stenographic

notebooks, which are detailed scientific journals.

The scientific works of Tsander can be grouped into the following main thematic areas: theoretical astronautics, space vehicles, reaction engines and piston aviation engines.

The materials on astronautics cover the basic problems of achievement of space flight, its reality and significance for man. In addition to the general problems, Tsander also studied many particular problems of astronautics: problems of astrodynamics are given significant coverage, including the selection of optimal trajectories for flights to other planets, the problems of correction of space trajectories, etc. Tsander turned a great deal of attention to problems of the utilization of aerodynamic forces in the atmospheric portions of an interplanetary flight. The works of Tsander dedicated to nonrocket principles of motion in space utilizing the pressure of light, electromagnetic and gravitational fields, are of particular interest today. Tsander also touched upon many important problems of astronautics, such as life support systems for astronauts during space flights and protection from the danger of meteorites. /76

The materials on space and rocket hardware include several theoretical works and a large number of documents related to the planning of an interplanetary spaceship-aeroplane, developed by Tsander in 1920-1928.

The most extensive section of the collection consists of materials on reaction engines, in which general problems are discussed related to the overall problem of the creation of LRE and jet engines, theoretical problems concerned primarily with thermodynamic calculations of engines of original designs suggested by Tsander himself. A significant portion consists of materials on rocket engines utilizing a combination of liquid and metallic fuel. Of great historical interest is the material related to the creation of the OR-1 motor, the first domestic reaction engine, differing in principle from earlier existing powder-burning rocket engines, and with the creation of the first domestic LRE, designed for installation on the OR-2 flight vehicle.

A significant portion of the collection consists of documents on piston engines. These documents were the result of the works of Tsander at aviation motor plants and at IAM, where Tsander took part in the creation of many of the first Soviet aviation engines. Very interesting are the materials related to the invention by Tsander of the oil-oxygen high pressure piston engine, designed for high altitude flights, particularly for installation on the first stage of his interplanetary spaceship-aeroplane.

A significant portion of the scientific works of Tsander has already been published. But many of these, of great scientific-historical and, possibly, practical interest, have never been prepared for publication. I refer basically to his shorthand materials, which require long and difficult work for interpretation. The shorthand records in his notebooks, record books, pads of paper and individual sheets in the Archives amount to some 160 storage units. The first work on their interpretation was performed at RNII in 1934-1935. At that time, some individual fragments of the various notebooks were interpreted, followed by full interpretation of individual materials which the administration of RNII considered to be the most important. Naturally, at that time most of the work on specific problems of astronautics were considered impractical and were not interpreted. Now, this work of interpretation has been begun again and is being successfully prosecuted by the Institute of the History of Natural Science and Technology, Academy of Sciences USSR.

The second group of documents in the collection consists of biographical material on F. A. Tsander, covering 1895-1933 (70 storage units). Among the personal documents are his birth certificate, diploma from the Riga City Practical School, his lesson (report) book and his diploma (with distinction) from Riga Polytechnical Institute, his certificate of completion of practice, documents relating to his military service, orders, pay calculation books and certificates of employment at "Provodnik" and "Motor" Plants and other places of employment, passport books and identification papers, documents of award for technical suggestions and other documentary materials. His membership /77
cards from the All-Russian Union of Metal Workers, All-Russian Association of Engineers, Engineering-Technical Section and other voluntary societies and organizations have been saved. This same group of documents includes forms filled out in Tsander's own hand, several versions of his autobiography, in which he describes his family life and also presents information verifying his priority in various inventions. In an appendix, Tsander presents a list of scientific work (published and unpublished) and inventions. One list notes the institutions, jobs, periods of employment and reasons for transfer of Tsander between 1914 and 1932.

There are few materials on Fridrikh Arturovich and his works -- only 27 files. Among these is the report of the Chief Engineer of "Motor" Plant, N. V. Okromeshko, and the Chief of the Production Section of the Aviation Department, P. A. Moisheyev, evaluating the interplanetary spaceship of F. A. Tsander; the reports of Professors V. P. Vetchinkin and V. I. Yakovlev on Tsander's work on interplanetary voyages; the report of the Chief of TPU Glavaviaprom Yermolov on F. A. Tsander's work in the Design Bureau of the Aviation Trust.

Among the materials on perpetuation of the memory of Fridrikh Arturovich are copies of the resolutions of the Bureau of the Praesidium of the CC of Osoaviakhim Union USSR honoring the memory of Tsander and supporting his family, a list of members of the Technical Commission for Development of the Works of Tsander; an estimate of 1934 of the expenses related to the fulfillment of the resolution of the CC Osoaviakhim of 6 May 1933 to develop the works of F. A. Tsander, the conclusion of the Commission for the Development of the Works of F. A. Tsander, a list of the works of Tsander, data for editing (with a list of the editors) and a list of the 32 works of Fridrikh Arturovich which were processed by the Commission.

A report by M. K. Tikhonravov to the Deputy Chief of RNII, G. E. Langemak, suggesting that the works of F. A. Tsander be published (January 1936) has been preserved; also preserved is a letter to the Director of the Scientific Research Institute, B. M. Slonimer, from "Oborongiz" Press (26 January 1940) agreeing to publish a collection of the works of F. A. Tsander amounting to 8-10 printed sheets. There are also rough materials on the preparation of the F. A. Tsander collection for printing (1 February 1940). Among these are a list of the articles of Tsander to be typed up, fragments of the plan for preparation of the manuscript, one version of a letter concerning inclusion of the Tsander collection in the publication plan of the planetarium and other documentary materials on the publication.

The completion of this work was prevented by the beginning of the second World War. However, at the end of the war the work was taken up again, and in 1947 the first collection of the scientific works of F. A. Tsander, edited by M. K. Tikhonravov, was published. In 1961 a second, greatly expanded edition of the works of F. A. Tsander, prepared on the instructions of S. P. Korolev, was published. Subsequently, a number of the works of Fridrikh Arturovich have been published by the Institute of the History of Natural Science and Technology, Academy of Sciences USSR.

The third group of materials reflects the activity of F. A. Tsander between 1920 and 1933, and consists of 92 storage units of the most widely varied nature. They include the correspondence of Tsander with government organs, scientific institutions and public organizations in the 20's and early 30's, the purpose of which was to secure the creation of a production base to realize the projects of the scientist, as well as expansion of scientific and technical propaganda in the area of reaction technology. Here also are the evaluations of scientists and officials concerning his scientific work.

This group also includes a number of documents characterizing the production work of F. A. Tsander at the M. F. Frunze (formerly "Motor") Plant. These documents describe Fridrikh /78

Arturovich as a highly qualified specialist, an active worker in the society. There are descriptions, reports, awards, as well as suggestions by Tsander to improve the organization of labor (we would say to introduce the scientific organization of labor), rationalizers' suggestions, reports by Tsander concerning his Socialist duties, documents indicating Tsander's participation in the shock workers movement, notes for lectures and reports, including lectures on political themes.

This group rather completely represents the materials on the practical work of Tsander in the area of rocket technology in the "pre-GIRD" period, based on the Institute for Aviation Motor Building (IAM) and TSAGI, and his activity on the creation of GIRD.

In this connection, we should note the as yet little studied working journal of Tsander (1930-1932). Of great interest is a document on the composition of the administration and the plan for the operation of the Bureau for the Study of Reaction Engines (18 June 1931), an agreement of 18 November 1931 concluded with the Bureau for Air Technology of NIS CS Osoaviakhim, and other documents. These documents can to a great extent be of assistance to researchers in restoring the missing links in the history of GIRD.

The editing and publishing activity of F. A. Tsander is represented in the collection by publication agreements and agreements to write and edit books and articles; materials and correspondence with various publishing houses concerning the editing, translation to German and publication of a jubilee collection of the works of K. E. Tsiolkovskiy; concerning the translation to Russian, editing and publication of the book of Professor G. Oberth "Rockets in Interplanetary Space"; invitations to conferences at various editing offices, letters from editors with requests to write articles on various themes, comments by F. A. Tsander made during editing of the works of other authors and other documentary materials.

The quantity of materials on pedagogic activity is small. They consist of lectures read by F. A. Tsander at higher educational institutions, schools, as well as lectures which he read on a volunteer basis in various clubs and at various courses. There are materials on the reading by Tsander of students' reports.

The fourth and smallest group of materials is the correspondence of F. A. Tsander. Here we find only 30 storage units covering the period from 1923 to 1932, a total of 56 letters.

The correspondence illustrates his scientific, personal and business relationships. Among his correspondents are great scientist and inventor K. E. Tsiolkovskiy, Professor V. P. Vetchinkin and N. A. Rynin, the writer and journalist

V. V. Stovichek, students at the Siberian Polytechnical School imeni Timiryazev in Tomsk, the Secretary of the Aviation Section of the Trans-Caucasus Osoaviakhim, Ye. V. Lutsenko and others.

Letters indicate that many of our scientists, engineers and students turned to F. A. Tsander for help and consultation. He always eagerly responded to these requests.

Let us speak very briefly concerning the group of illustrative materials, consisting primarily of photographs. Here is a family photograph, several photographs from his youth, photographs where F. A. Tsander is working among his colleagues at GIRD and a few other group photographs.

This, in the most general of terms, is the content of the F. A. Tsander collection.

For any study of the life and activity of Tsander, in addition to the materials of his personal collection, one must also utilize the reports on tests, drawings, plans and photographs of the "10" and OR-2 engines, the GIRD-X rocket, the RP-1 rocket plane, the recollections of GIRD workers and other materials stored in the Archives of the Academy of Sciences in the collection on the history of Soviet rocket technology. /79

At the present time, work on the documentary materials of the collection is continuing, and its scientific description is being prepared for publication. However, we cannot consider the collection to be complete. Many other materials are not on hand -- letters by Tsander, reports on his work, photographs, perhaps even articles, inventions, notes for lectures. They must be added to the collection.

We hope that all of the manuscript heritage of Fridrikh Arturovich Tsander will find its way to his personal collection in the Archives of the Academy of Sciences USSR.

The workers of the Archives express their gratitude to Yu. V. Biryukov, V. M. Komarov and I. N. Tarasenko for their technical consultation and assistance in processing the collection.

II

THEORY AND DESIGN OF ENGINES AND FLIGHT VEHICLES

THE THEORY OF OPTIMAL DIRECT FLOW ROCKET ENGINES WITH AIR-CHAMBER AFTERBURNERS

Yu. M. Annushkin, L. N. Druzhinin and V. A. Sosunov

The use of the air as an oxidizer in engines significantly /80
improves their economy in comparison to purely rocket system. F. A. Tsander returned to this idea repeatedly [1].

It is possible in principle to improve the economy of ordinary rocket engines by adding an ejector nozzle attachment, in which the combustion products of the rocket fuel are mixed with air and at the same time expand in the common nozzle. The power plant in this case may consist of a large number of rocket engines located around the periphery of the body of the rocket, which also serves as the central body of the nozzle [2, 3].

A more significant increase in specific impulse is achieved by using a direct-flow rocket motor (DRM), in which the rocket engine acts as a gas generator, producing the products of combustion, containing an excess of fuel and exhausting under high pressure into the direct flow loop. The processes of mixing and combustion in the DRM may be separated or may occur simultaneously in a common afterburner [4, 5]. In this work, we study engines with combined processes of mixing and combustion. The specific impulse of engines in this group may be significantly higher than in ordinary rockets, reaching 1000-1200 sec using ordinary hydrocarbon fuels [3].

As in rocket engines, in DRM it is possible to use solid, liquid or hybrid fuels [3]. The use of liquid fuel allows optimal regulation of the ratio between fuel and air over the trajectory of the flight, as well as the consumption of fuel and oxidizer. Solid fuels provide the least possibility for regulation. In this case, one can program the desired change in fuel consumption by selecting the shape of the charge.

The characteristics of DRM depend strongly on the composition of the fuel. With high relative oxidizer consumption, corresponding to high specific thrust of the gas generator (maximum "natural" impulse J_r), the stoichiometric coefficient L_0 and the calorific value H_u of the fuel in air are minimal. In this case, with lower economy, the forward thrust of the DRM will be maximal. As the oxidizer consumption decreases, H_u and L_0 of

the fuel increase and the economy of the DRM improves, but the forward thrust is reduced due to the deterioration of the ejection properties of the fuel (J_{rr} decreases). The minimum feed of oxidizer is determined by the conditions of stable combustion, gasification and full extraction of the combustion products of the gas generator. /81

Due to the large number of parameters which can be selected or regulated, it becomes important to make the optimal selection of the dimensions of the gas-carrying tract and operating modes of the DRM. In this article, using the simplest DRM plan with nonregulated cross section of the air collector and nozzle, we shall analyze some possibilities and trends for this optimization, namely:

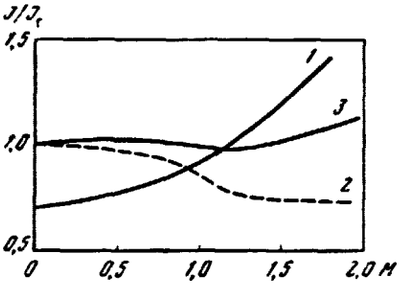


Figure 1. Relative Specific Effective Impulse of a DRM in the Launch Sector. 1, Independent Launch DRM; 2, Launch Rocket Engine Operating, DRM Off; 3, Simultaneous Operation of Launch Rocket Engine and DRM

1) Expedient use of DRM during the launch section of the flight (M = 0-1.5);

2) Rational utilization of the ejection effect of the rocket fuel;

3) Optimal organization of the fuel afterburner process in the DRM air-breathing section.

The low efficiency of ejection compression reduces the effectiveness of the use of DRM immediately at the launch. Calculations have shown that in the range of flight velocities corresponding to M = 0-1, the specific impulse of a DRM is lower than that of a rocket motor per unit of fuel consumed, particularly if we consider the actual losses of total pressure in the unregulated air collector (Figure 1). Similar results were produced in [6]; however, according to the data of this work, DRM become more efficient than ordinary rocket engines at M > 0.5.

If the rocket is designed for the use of DRM as the primary engine at M > 1.5-2, where the DRM is most efficient, while acceleration in the range from M = 0 to M = 1.5-2 is by a special rocket accelerator engine, it is most efficient to turn on the DRM at the launch. This eliminates the additional drag which would arise as air flows through the nonfunctioning DRM and at the same time increases the economy of the power plant as a whole.

The degree of influence of the specific impulse of the fuel on the individual parameters of an ideal regulated DRM due to the ejection effect depends on the M number of flight and the

excess air factor

$$\alpha = G_B/G_T L_0.$$

As the flight speed increases, the increase in pressure upon deceleration of the incoming stream, which determines the thermal efficiency of the cycle and the economy of the DRM increases, while the significance of the ejection compression of air decreases and where M > 2.5 it becomes practically useless. However, the influence of ejection on forward thrust is retained up to high flight speeds, since the throughput capacity /82
of the engine section is proportional to the available total pressure (Figure 2a). The mechanism of the influence of ejection on the characteristics of acceleration DRM with nonregulated cross section of the flow-carrying channel is somewhat different. With an increase in the proportion of oxidizer in the fuel g_{0k} in the initial sector of acceleration and correspondingly with great ejection compression of the air, a flow-carrying portion can be planned which is more favorable for high flight speeds. If then with increasing speed the fraction of oxidizer in the fuel is reduced, the specific impulse of the DRM, which is comparatively low at the beginning of the trajectory, increases rapidly and at a certain value of M even exceeds the specific impulse of the DRM designed for a constant ratio of oxidizer to fuel (Figure 2b).

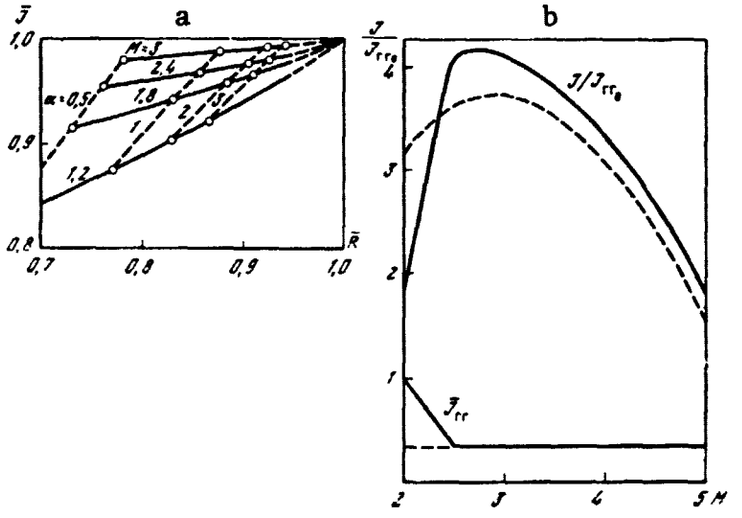


Figure 2. Influence of Ejection on Characteristics of DRM. a, Ideally Regulated Motor: $\bar{J} = J_{J_r} = 0/J_{DRM}$, $R = R_{J_r} = 0/R_{DRM}$; b, Unregulated Engine; J_r, g_{0k} = const (dotted line)

In comparison with rocket engines, DRM are heavier, so that they provide a savings only if the savings in fuel weight is sufficient to cover the increase in structural weight. A significant portion of the weight of the DRM consists of the air combustion chamber. Obviously, as the length of the chamber increases, the effectiveness of afterburning of the fuel increases, the required fuel reserve decreases, but the structure becomes heavier. Thus, in planning DRM one of the most important tasks is the selection of the optimal afterburner chamber length, for which the total weight of fuel and metal is minimal. We present below some possibilities for this optimization.

The products of decomposition of the fuel in the gas generator of the DRM may consist of combustible and noncombustible gas components (for example H_2, CO, CO_2, Ch_4, etc.), may contain condensed combustible and noncombustible particles (carbon, metals, oxides, etc.)[1]. If we ignore the case in which the decomposition products include comparatively slowly burning particles (for example boron, aluminum, 6%), the afterburning process will be limited primarily by diffusion mixing of the fuel jet with the air [6]. This is indirectly indicated, for example, by the change in the length of the visible flame, proportional to the diameter of the gas generator nozzle. Thus, the analysis of the process of afterburning of the fuel in the air channel of the DRM in many cases can be based on a model of a quasigas diffusion flame developing in a turbulent stream of the products of primary combustion of the fuel components in the gas generator (generally two-phased). /83

The method of analysis used leads to two conclusions:

1) Modeling of the process in a DRM is possible by retaining geometric similarity of the air channel;

2) Direct comparison of the effectiveness of the process in single-nozzle and multiple-nozzle engines is possible if the equivalent lengths of the combustion chamber and relative areas of the cross sections of the channel are equal (Figure 3).

By the equivalent length of the combustion chamber, we shall mean the relative length of the combustion chamber of a multiple-nozzle DRM, expressed in diameters of the equivalent

[1]Solid particles are formed upon primary combustion of solid rocket engine fuel in the gas generator, for which it is characteristic that there is a low content of oxidizer (for example, ammonium perchlorate 30-50%), plus organic binder (10-15%) and a high content of metal (aluminum, magnesium, boron up to 40-60%) [2, 4].

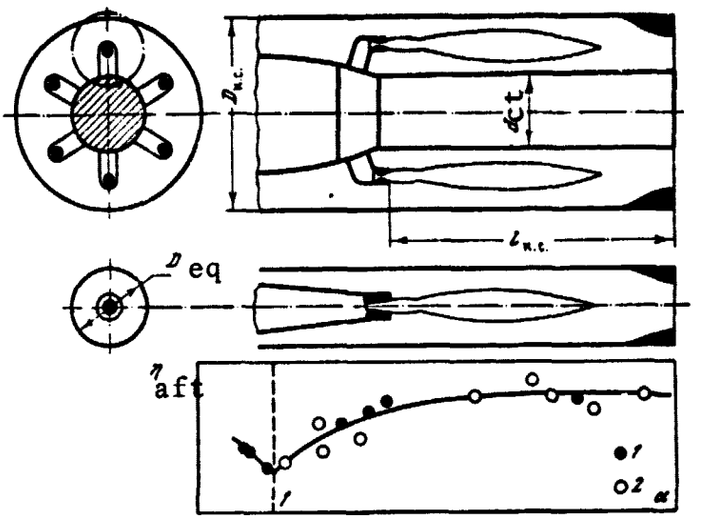


Figure 3. Multiple-Nozzle (1) and Equivalent Single-Nozzle (2) Engines and Completeness of Afterburning of Fuel in Them ($\bar{L}_{eq}$ = idem)

single-nozzle engine:

$$L_{eq} = L_{kc}/D_{eq} = (L_{kc}/D_{kc})(\sqrt{N_c/(1 - \bar{d}_{ct}^2)})$$

where N_c is the number of nozzles of the gas generator: $d_{ct} = d_{ct}/D_{kc}$.

This brings up the possibility of significantly reducing the length and lightening the combustion chamber of the DRM without reducing the efficiency of combustion of fuel by constructing a multiple nozzle gas generator (a complication in design, obviously resulting in some increase in weight). The length of the chamber with constant air flow through the motor is reduced in inverse proportion to the square root of the number of nozzles. The possibility of reducing the length of the chamber of a DRM by increasing the number of nozzles of the gas generator has been repeatedly discussed in the literature [6, 7]. The data presented on Figure 4 from an experiment confirm the practical identity of the processes of combustion in single-nozzle and multiple-nozzle models where $\bar{L}_{eq}$ = idem. /84

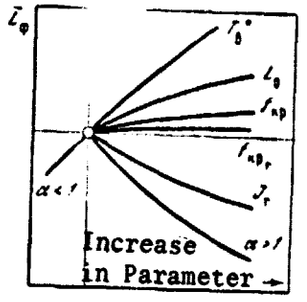


Figure 4. Characteristic Parameters of the Diffusion Flame in a DRM Chamber

The air chamber length required for full combustion of the fuel is determined by the length of the diffusion flame formed in the stream of products of primary fuel combustion, which depends on the type of fuel, operating mode of the chamber, relationship of the diameters of the chamber, reaction nozzle and gas generator nozzle. The intensity of mixing of the unburned gas turbulent stream with the accompanying open air stream is determined by the ratio of velocities and the densities of the streams being mixed [8]. The length of the open flame, furthermore, depends on the stoichiometric coefficient of the fuel, which determines the relative quantity of air which must diffuse to the axis of the stream at the end of the flame. The limited space in the combustion chamber of the DRM, in turn, effects the diffusion flame, which is determined by the presence of a longitudinal pressure gradient in the chamber and fixed flow rate of air in it. This facilitates significant elongation of the flame at low excess air factors, namely where $\alpha < \tilde{\alpha}_\phi$, where $\tilde{\alpha}_\phi \approx 2.5\text{-}1.5/L_0$ -- the mean excess air factor in the turbulent stream in the cross section at the end of the flame. Where $\alpha < \tilde{\alpha}_\phi$, the outer boundaries of the turbulent stream of burning fuel reach the walls of the combustion chamber before combustion is completed in the flame on the axis of the stream. Theoretically, where $\alpha \to 1$, the length of the flame approaches infinity, since all of the air must be mixed with the fuel. Where $L_0 > 1.5$, the value of $\tilde{\alpha}_\phi$ varies within narrow limits -- from 3.5 to 2.5.

One peculiarity of the process of diffusion combustion in a DRM chamber is the neutral relationship of the parameters of the streams in the input and output cross sections of the chamber, since the reaction nozzle and the gas generation nozzle operate in the "blocked" mode. In connection with this, the conditions of mixing of the fuel and the length of the flame are fully determined by the operating mode of the engine (excess air factor α and air stagnation temperature T_B^*), type of fuel used (L_0, J_{rr}), relative areas of critical cross sections of reaction nozzle and gas generation nozzle (f_{kp} and $f_{kp.r}$). The qualitative nature of the influence of these parameters on flame length, revealed in calculations for a group of homogeneous fuels, is shown in Figure 4. The excess air factor influences the form of the flame in the areas $\alpha > 1$ and $\alpha < 1$ qualitatively oppositely (in the area $\alpha < 1$, the leading edge of the flame is attached not to the axis, but rather to the walls of the chamber).

The completeness of combustion of fuel in the air chamber of the DRM depends on the ratio of the actual length and length of

the diffusion flame in the jet of fuel, characteristic for the assigned parameters of the engine and fuel. The total completeness of combustion of the fuel in the engine η_r can be determined from the ratio of the actual heat liberation to the maximum possible heat liberation upon combustion of 1 kg of fuel Q_{max}, which where $\alpha \geq 1$ is equal to its heat capacity H_u, while where $\alpha < 1$ it is approximately determined by the formula

$$Q_{max} = (H_u - Q_r)\alpha + Q_r,$$

where Q_r is the heat liberated upon combustion of 1 kg of fuel in the gas generator.

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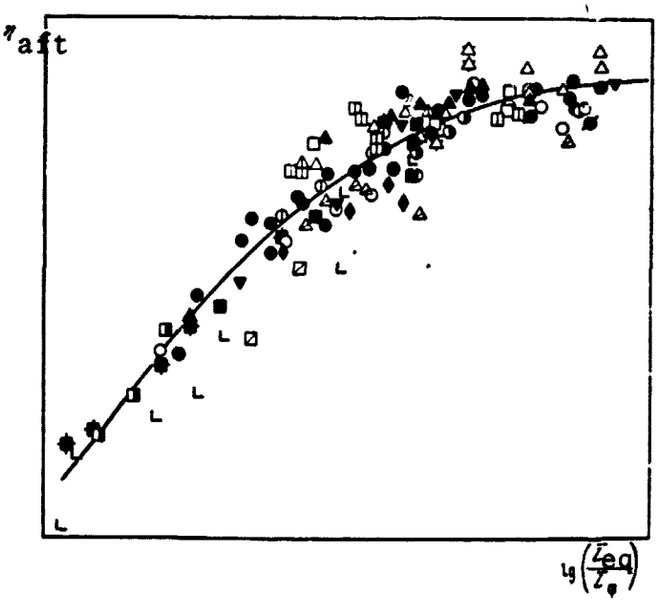


Figure 5. Generalized Dependence of Effective Completeness of Afterburning of Fuel

The completeness of combustion of fuel in the air chamber (with completed combustion in the gas generator) is expressed through the overall completeness of combustion

$$\eta_{aft} = \frac{\eta_r - \bar{Q}_r}{1 - \bar{Q}_r} \quad \left(\bar{Q}_r = \frac{Q_r}{Q_{max}}\right).$$

We can assume that there is a universal curve for combustion of homogeneous fuels over the length of the air combustion chamber, expressed by

$$\eta_{aft} = f\left(\frac{L}{L_\phi}\right),$$

where η_{aft} are the experimental values of effective completeness of afterburning, produced with various equivalent combustion chamber lengths $\bar{L}_{eq}$ in various operating modes; $\bar{L}_\phi$ is the calculated flame length (in relationship to the equivalent diameter of the combustion chamber), found for the condition of the experiment.

The existence of this universal dependence (Figure 5) indicates the correctness of the theoretical assumptions which form the basis of calculation of $\bar{L}_\phi$, and allow us to use it to estimate the effectiveness of combustion of the fuel selected in an engine considering the flight mode, assigned fuel consumption and air flow rate, and specific geometric characteristics of the combustion chamber. In this calculation, it is sufficient to estimate the relative change of flame length in flight (i.e., the ratio of $\bar{L}_{eq}/\bar{L}_\phi$) as a function of the parameters indicated above without studying the shape and structure of the flame.

The change in completeness of combustion of fuel in a DRM typical for purely diffusion combustion as a function of operating mode and flight mode is shown in Figure 6. The characteristic decrease in completeness of combustion with an increase in flight velocity (increase in T_B^*) is explained by the unfavorable influence of an increase in relative air velocity entering the chamber and a decrease in its relative density on the process of mixing of fuel and air [8]. /86

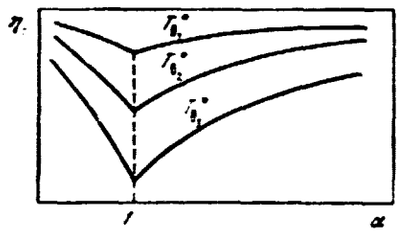


Figure 6. Typical Change in Completeness of Fuel Combustion in a DRM ($T^*_{b_1} > T^*_{b_2} > T^*_{b_3}$)

The number of nozzles of the gas generator of a DRM is limited by reasonable structural considerations. If the number of nozzles of a gas generator in a specific DRM is fixed, the possibility arises of optimizing the operating mode of the engine in flight by selecting the geometric characteristics of the chamber in order to produce the minimum total weight of fuel and metal.

Characteristic dependences of the optimal design values of excess air factor α_{opt} on M number of

flight for mechanically unregulated acceleration DRM, determined with the condition of the maximum increase in velocity of the rocket per unit of fuel mass consumed at each point on the trajectory, are presented in Figure 7. The graph also shows the nature of the change in completeness of combustion of the fuel and the specific impulse of these engines (instantaneous values of completeness of combustion calculated by method outlined above). The effective impulse has a characteristic maximum in the area of M ≈ 3 (see also [9, 5]). At the beginning of acceleration, where M = 2-2.5, when the maximum possible thrust is required, the values of α_{opt} of an engine with unregulated flow channel decrease with increasing velocity so that the maximum possible coefficient of restoration of full pressure in the air collector $\sigma_d = \sigma_{dmax}$ ("thermal regulation") is retained. Decreasing the completeness of combustion of the fuel with values of α near 1, particularly with increasing stagnation temperature of the air T_B^*, leads to the fact that the values of α_{opt}, without reaching unity, begin to increase at a certain flight velocity. At a sufficiently high velocity and altitude (M > 4-5), in order to produce the necessary excess thrust it is desirable to go over to the area of modes with α < 1.

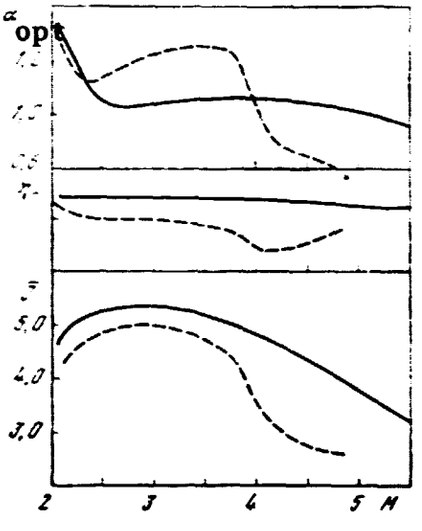


Figure 7. Optimal Excess Air Factor, Completeness of Combustion and Specific Effective Impulse in a DRM as Functions of Flight Velocity. $*_{eq}$ (Dotted Line); $\bar{L}_{2eq} = e\bar{L}_{1eq}$ (Solid Line)

This nature of the change in the optimal operating mode of a DRM with flight velocity is particularly clearly seen at low equivalent combustion chamber length, for which the completeness of fuel combustion and specific impulse are significantly lower (see Figure 7).

Obviously, due to the opposing influence of relative chamber length on the effectiveness of the combustion process and on the weight of the structure, for any desired increase in rocket velocity one can select a certain optimal chamber length, for which the total weight of fuel and metal is minimal. /87

*Translator's note: Omitted in original text.

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THE POSSIBILITY OF USING THE CHEMICAL ENERGY OF THE BONDING OF METALS WITH NITROGEN IN THE AIR IN JET ENGINES

V. M. Khaylov

One of the ideas of F. A. Tsander was the utilization of metals as fuel for jet engines installed on space vehicles. In his work "The Problem of Flight by Means of Reaction Apparatus," Tsander suggested that "For jet engines, Li and B are most suitable due to their low atomic weight" [1]. The foresight of Tsander has been realized. At the present time, fuels consisting of compounds of boron with hydrogen and lithium are considered quite realistic for jet engines [2]. Later, in 1951, I. A. Merkulov set forth the idea of increasing the thrust of a jet engine by feeding an additional mass -- an inert substance, an excess quantity of fuel or additional fuel plus oxidizer -- into the combustion chamber [3, 4].

In the present work, we analyze a further development of the idea of Tsander -- the possibility of increasing the thrust of direct-flow jet engines intended for acceleration of rockets by utilizing the chemical energy of metal compounds as they bond with nitrogen in the air. It will be demonstrated below that, according to calculated estimates, the use of the effect of the formation of nitrides of certain metals (B, Be, Al, Mg) in combustion of extremely rich fuel mixtures (with a shortage of oxygen) can significantly increase the performance of a direct flow jet engine while maintaining satisfactory economy. /88

We know from the literature [5, 6] that elements of groups II and III of the periodic table, in the second and third periods (Be, Mg, B and Al), have the capability when heated for exothermic interaction with gaseous nitrogen:

$$3Be + N_2 \rightarrow Be_3N_2 + 135 \text{ kcal}, \quad (1)$$

$$3Mg + N_2 \rightarrow Mg_3N_2 + 110 \text{ kcal}, \quad (2)$$

$$2B + N_2 \rightarrow 2BN + 122 \text{ kcal}, \quad (3)$$

$$2Al + N_2 \rightarrow 2AlN + 152 \text{ kcal}. \quad (4)$$

Reaction (2) begins to occur effectively at temperatures over 560 C, reactions (1) and (4) at temperatures over 800-900 C, reaction (3) -- at 1200 C [5]. The nitrides formed as a result of these reactions are solids, generally refractory. For example, the melting point of AlN and Be_3N_2 at normal pressure is 2200 C, the melting point of BN is 2700 C.

It has also been reported in the literature that nitrides can be formed not only upon interaction with pure nitrogen, but also upon combustion in the air with a deficiency of oxygen. For example, it is reported in [5] that combustion of magnesium where $\alpha < 1.0$ leads to the formation of both oxides and nitrides of Mg.

Since the heat production of these reactions is significantly lower than the reactions of combustion of hydrocarbons or hydrogen in oxygen[1], it is natural to expect that this effect will be of practical interest only under conditions of operation of a jet such that the available quantity of oxygen in the air is insufficient for creation of the required engine thrust or when the maximum useful work must be obtained from a limited quantity of air. The energetic estimates of the possibilities of these reactions performed in this work, supported by the results of thermodynamic calculations of the combustion of borohydrides in air where $\alpha \leq 1$, confirm these considerations.

In order to compare the thermal effects which are possible due to the formation of nitrides upon combustion of Mg, Al, B and Be with a shortage of oxygen, we performed estimated calculations of the heat capacity of these fuel-air mixtures over a broad range of weight ratios of air to fuel (G_a/G_f). The results produced are presented in Figure 1. It was arbitrarily assumed in this case that in the area of lean mixtures, the combustion products would consist of the full oxide of the fuel (metal), nitrogen and unreacted oxygen; in the area of richer mixtures, all of the oxygen would go into formation of the oxide, and the remaining portion of the fuel would bond with nitrogen, /89

Oxide	kcal/mol	J/kg	Reference	Nitride	kcal/mol	J/kg	Reference
BeO	143,1	$14,99 \cdot 10^6$	[7]	Be_3N_2	135	$31,12 \cdot 10^6$	[8]
MgO	143,8	$24,28 \cdot 10^6$	[7]	Mg_3N_2	110	$46,5 \cdot 10^6$	[9]
B_2O_3	305,8	$89,10 \cdot 10^6$	[7]	BN	61	$6,34 \cdot 10^6$	[7]
Al_2O_3	400,4	$170,9 \cdot 10^6$	[7]	AlN	76	$13,64 \cdot 10^6$	[7]

forming the nitride, as the fuel mixture is enriched, the quantity of free nitrogen decreases to 0 (stoichiometric ratio to nitrogen), and subsequently the mixture consists of the oxide, nitride and unreacted fuel. The heats of formation of the corresponding oxides and nitrides included in the calculation are presented in the table. The data on the heat capacity presented in Figure 1 are related to 1 kg of combustion products mixture.

[1] The thermal effect of the reaction $B + \frac{1}{2}N_2 \rightarrow BN$ is 3600 kcal per kg of B, while the reaction $Al + \frac{1}{2}N_2 \rightarrow AlN$ = 2800 kcal per kg.

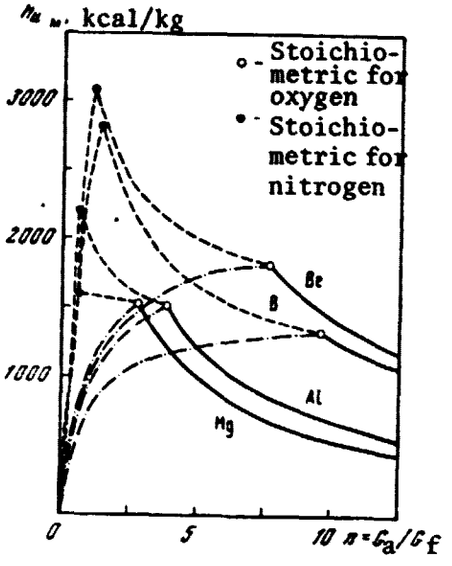


Figure 1

Analysis of Figure 1 indicates that the stoichiometric ratio for nitrogen for all of the metals studied is in the area G_a/G_f = 0.5-1.5. The stoichiometric relationships for nitrogen correspond to the maximum H_{um} of each of the elements studied.

The graph presented allows us to compare the metals in question from the standpoint of the expected engine thrust, since the higher H_{um} for a given G_a/G_f, the greater the thrust which can be realized per unit of air consumption. Obviously, the greatest energetic effect can be expected from the formation of the nitrides of Be and B (H_{um} > 2000 kcal/kg with G_a/G_f < < 5.0). Probably, the use of Al and Mg in this area of modes is less desirable due to the significantly lower possible values of H_{um}.

The analysis which we have presented is based on rather arbitrary assumptions concerning the course of the chemical reactions. Therefore, in order to confirm the results produced for fuel based on boron, a full thermodynamic set of calculations was performed for the processes of combustion considering the formation of all possible chemical compounds, as well as calculation of the processes of expansion of the combustion products formed in the nozzle. We analyzed not pure boron, but rather its hydrides -- pentaborane B_5H_9 and diborane B_2H_6. This replacement was performed for the following reasons. As pure boron is burned in the area of stoichiometric relationships for nitrogen (if we return to the reaction plan analyzed above), the products of combustion should consist almost completely of solid nitride and oxide, condensing at T < 2500 C. Therefore, the gaseous working fluid, capable of realizing the thermal effect produced in the nozzle of the engine will be almost totally absent. We must therefore study a fuel composition which is capable of yielding a significant quantity of usable gas in the area of the stoichiometric relationship for nitrogen. The addition of hydrogen to the fuel based on boron allows us to solve this problem.

In performing thermodynamic calculations, it was assumed /90
that chemical and thermodynamic equilibrium were established in the combustion chamber, and that the gas exhausted from the nozzle isentropically, without losses resulting from the lagging

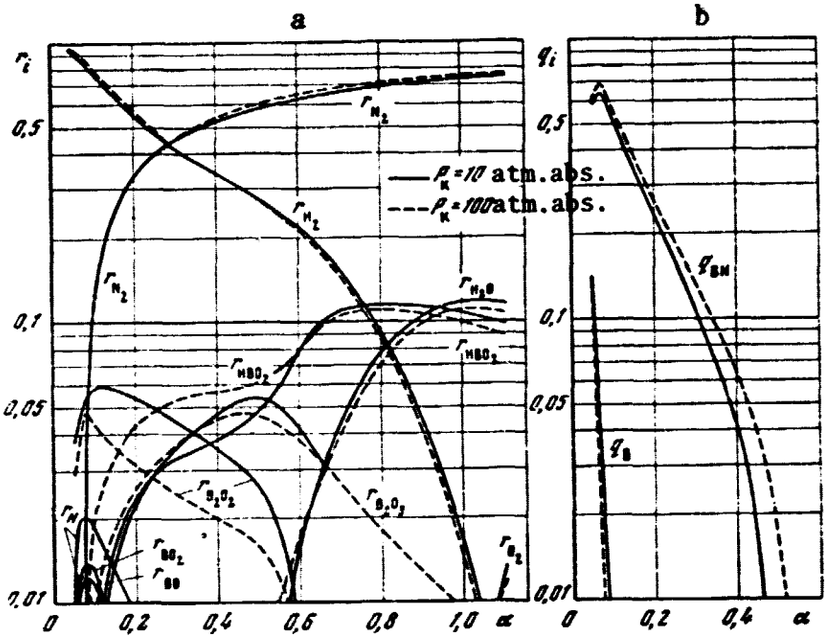


Figure 2

of particles behind the gas in the two-phase stream. The thermodynamic properties of the products in question were taken from handbook [7]. The possibility of formation of 31 gaseous substances was considered (H_2, O_2, O_3, OH, HO_2, H_2O, H_2O_2, N_2, N_3, NO, NO_2, N_2O, NH, NH_2, NH_3, N_2H_4, HNO, B_2, BO, BO_2, B_2O_2, BN, HBO, HBO_2, H_3BO_3, B_2O_3, BN, B, N, O, H), plus three condensates: B_2O_3, BN and B. The calculation was performed using a specially developed program and an M-20 computer. During calculation of the products of combustion of pentaborane in air, difficulties were encountered, related to the fact that the program did not allow us to calculate the points at which the condensate is simultaneously in the solid and liquid phases. In diborane-air mixtures, this phenomenon was not observed, and therefore the main portion of the calculations was conducted for this fuel. The calculations were performed over a broad range of change of relationship of the components (excess air factor as oxygen α varied between 0.05 and 1.1) for two values of chamber pressure P_k = 10 and P_k = 100 atm and with various temperatures of air entering the combustion chamber.

Figure 1, as an example, shows the compositions of the combustion products of diborane in air, calculated for various values of α at pressures P_k = 10 and P_k = 100 atm with a temperature of the air entering the chamber of 20 C. Figure 2a shows

the volumetric fractions of the gaseous components of the combustion products r_i, while Figure 2b shows the weight fractions of the condensed components q_i.

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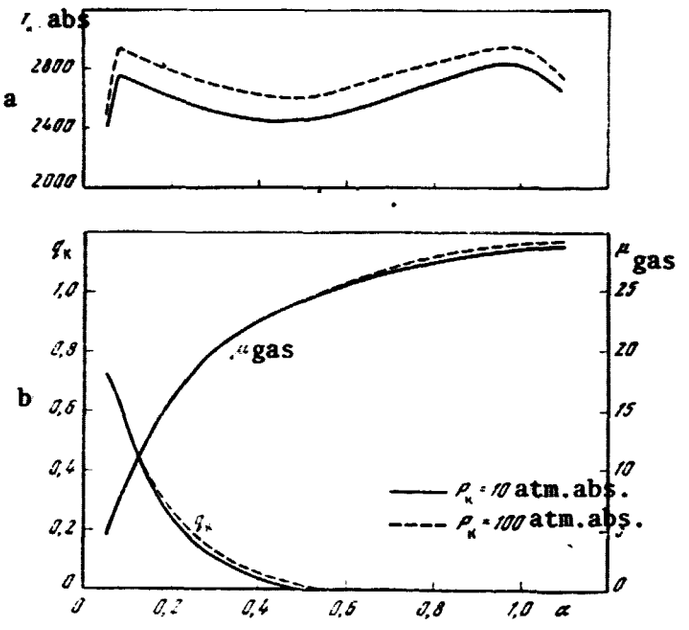


Figure 3

Figure 3 shows the temperatures in the combustion chamber T_k calculated for this case, the total gravimetric quantity of condensed phase q_k and the apparent molecular weight of the gaseous portion of the combustion products μ_r.

Analysis of Figures 2 and 3 a, b shows that the composition of the combustion products, calculated on the assumption of chemical equilibrium, in general features follows the arbitrary plan adopted above. The combustion products in the area $\alpha < 1.0$ contain primarily nitrogen, water, hydrogen and solid boron nitride. The difference from the assumptions accepted earlier is that in the gas phase of the combustion products according to the calculations there is a significant quantity of metaboric acid HBO_2 and the dimer of B_2O_2. Boron oxide, due to the high temperatures ($T_k > 2500$ K) is in the gaseous state. In the area located to the left of the stoichiometric relationship for nitrogen ($\alpha \leq \leq 0.074$), as was assumed, unreacted solid boron is ejected. The content of the remaining components of the combustion products is slight, not over 1.5-2%.

The thermal effect of the formation of boron nitride leads, as was to be expected, to the appearance in the area of the stoichiometric relationship for nitrogen of a second temperature maximum (together with the ordinary temperature maximum in the area of the stoichiometric relationship for oxygen $\alpha \approx 1.0$). Similar results were produced in calculating the products of combustion of diborane in heated air (T_a = 300-4000 K). An increase in the temperature of the air fed into the combustion chamber leads to a significant degree of dissociation of the combustion products only in the area of $\alpha = 1.0$. In the area of the stoichiometric relationship for nitrogen, an increase in air temperature right up to 2500 K almost does not increase the degree of dissociation of combustion products and the second temperature maximum is retained. This allows us to hope that the thermal effect of formation of nitrides will appear in the engine at higher flight velocities, when the stagnation temperature of the air reaches significant values ($M_f > 5.0$). Calculations have shown that pentaborane also has two temperature maxima. However, the "nitrogen" maximum of pentaborane is cut off, due to the fact that where $\alpha < 0.25$, the temperature of the combustion products reaches 3000 K (melting point of boron nitride) and BN in this area is present in the products partially in the liquid and partially in the solid states. /92

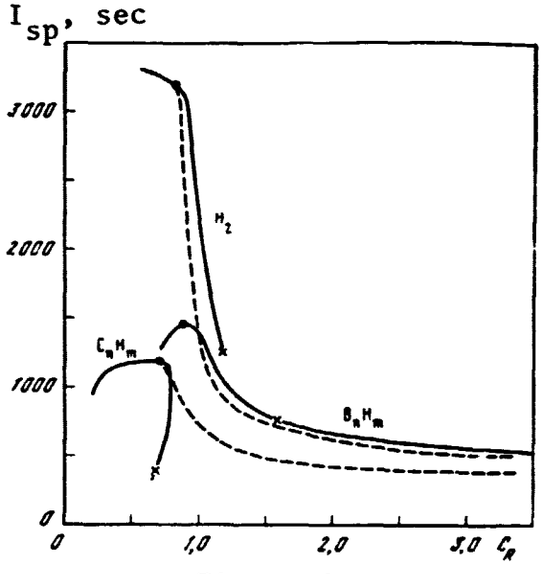


Figure 4

In order to estimate the possibility of using the thermal effect of formation of metal nitrides in forced direct-flow jet engines, we performed thermodynamic calculations of the process of combustion and expansion of the combustion products in the nozzle (using the equilibrium plan described above).

Figure 4, as an example, shows the calculated characteristic of an ideally regulated direct flow jet engine in the coordinates' specific impulse I_{sp} vs. thrust coefficient C_R, using diborane as a fuel. Calculations were performed for M_f = 6.8 and flight altitude 26 km (which corresponds to the arbitrarily selected conditions P_k = 10 atm and T_k = 2000 K with the full pressure restoration coefficient in the air collector and combustion chamber σ^* = 0.12 included in

the calculation). Here also for comparison we present the characteristics of direct flow jet engines burning hydrogen and kerosene. The dotted curves correspond to the engine forced by injection of the boron oxidizer into the combustion chamber -- oxygen (α_ε = 1.1).

Analysis of Figure 4 indicates that the economy of the direct flow engine operating with the boron-hydrogen fuel in the area of high thrusts is near the economy of hydrogen direct flow jet engines forced with oxygen and significantly higher than the economy of a kerosene jet engine with oxygen forcing[1]. The calculations also showed that the economy of a direct flow engine operating with pentaborane is 7-13% lower than the economy of a diborane engine (not shown in Figure).

Considering that the density of boron-hydrogen fuels is several times the density of liquid hydrogen, we can assume that the use of direct flow engines burning boron-hydrogen fuels in the area of high M numbers in the case of equilibrium processes in the chamber and nozzle of the engine will allow a significant decrease in the size and weight of the fuel tanks in comparison to hydrogen direct flow engines forced with oxygen, and will increase the effectiveness of the entire flight vehicle. /93

The similarity of the actual process in the combustion chamber and engine nozzle to the equilibrium plan when operating in the area $\alpha < 1.0$ on fuel mixtures containing nitrogen and metals needs experimental testing. There is reason to hope that, due to the high combustion temperatures in the area of the stoichiometric relationships for nitrogen, equilibrium in the combustion chamber will be achieved. In this respect, there is interest in the results of certain investigations performed in recent times, in which the reactions between metals and nitrogen occurring in flames were studied. In [10, 11], based on experimental studies of the interaction of hydrazine and borane, performed in small-scale burners, the possibility in principle of organization of effective interaction between boron and nitrogen in the borane-hydrazine system was demonstrated, in spite of the absence of the traditional reactions of oxidation in the flame.

The degree of equilibrium and the depth of reaction of Al, Be, B and Mg, as well as Zr, with nitrogen was studied in [12]. It was determined, in particular, that in a calorimetric bomb, as the products of decomposition of lead azide interacted with powders of the metals listed, a significant degree of heat liberation occurred due to the formation of the nitrides of

[1] Forcing of a direct flow engine burning kerosene or hydrogen by adding a mass (modes $\alpha \approx 0.3$), recommended in [3], is less effective for the M_f number in question.

these elements. The heats of formation of the nitrides calculated on the basis of the experiments performed agree with great accuracy with the literature data, which indicates the high effectiveness of the occurrence of the reactions in these conditions.

In [13], a study was made of the flash point of certain metals in the powdered state in gases with various chemical compositions. The measurements were performed using thermocouples placed in a mass of the powdered substance. The following ignition temperatures were produced for powders in an atmosphere of nitrogen: lithium 410 C, beryllium 527 C, boron 1440 C, zirconium 780 C. It is noted in this work that in an atmosphere of pure nitrogen, the maximum quantity of heat is liberated upon combustion of boron and beryllium.

Based on these data, we can assume that the achievement of chemical equilibrium in the combustion chamber of engines using the thermal energy of the formation of nitrides is probably a realistic hope. However, it is possible that this process will require special organization of the process which occurs in the combustion chamber.

We should also note that due to the presence in the combustion products of a large quantity of solids (up to 50% by weight), significant losses of thrust due to the nonequilibrium nature of the exhaust from the nozzle of the two-phase combustion products is unavoidable. It is impossible to determine these losses in the present work due to the lack of data on the dispersion of the BN powder formed as these reactions occur. This problem requires special study.

In conclusion, the author expressed his gratitude to A. I. Morozkin, who wrote a special program and used it to calculate the products of the combustion of borane and hydrogen in air.

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THE POSSIBILITY OF USING THE STRUCTURAL ELEMENTS AS FUEL AND OTHER PECULIARITIES OF HYPERSONIC RAMJET ENGINES

A. T. Berlyand, V. I. Penzin and V. A. Eysmont

The idea of F. A. Tsander of the utilization of the structural elements of a flight vehicle and engine as fuel [1] can be realized in a hypersonic ramjet engine. In this case, there is no need to organize a special technological process to grind up the structural elements to powder and transport the powder to the combustion chamber of the engine. The walls of the flow-carrying portion of the engine are quite long and are washed by a stream with a high velocity head and temperature, and can be made of an oblating material which will be carried away in layers during flight according to a predetermined rate, with subsequent combustion in the combustion chamber of the engine.

The problem of making a ramjet engine with combustible elements in the channel can be divided into two parts. First of all, the problem of selection of the material and assurance of its effective combustion. The first experimental and calculation investigations of the combustion of solid fuels consisting of the material of the walls (polymethylacrylate and nylon) at even supersonic speeds in a combustion chamber [2] have shown the technical possibility of this process. As we can see from Figure 1, there is rather good agreement between calculated and experimental increments of the pressure factor $\Delta C_{pr} = C_{pr} = C_{px}$ due to combustion. Here C_{pr} is the pressure factor with combustion; C_{px} is the pressure factor without combustion; P_0T_0 is the pressure and temperature in the receiver; M_0 is the M number at the exit cross section from the nozzle; M_1 is the M number over the plate; G_T is the gravimetric flow rate of polymethylacrylate with combustion; G_a is the gravimetric flow rate of air through the channel. /95

Second is the problem related to the selection of the rule of change of the shape of the flow portion of the channel, providing the maximum thrust characteristics of the engine, determination of the parameters of the gas stream in the channel as the shape alters and, finally, estimation of the changes in aerodynamic characteristics of the flight vehicle, since when a ramjet is used, the flight vehicle and engine are inseparably related [3].

The present work relates to the second portion of the problem and is dedicated primarily to the method of calculation of characteristics of such an engine, consideration of the specifics

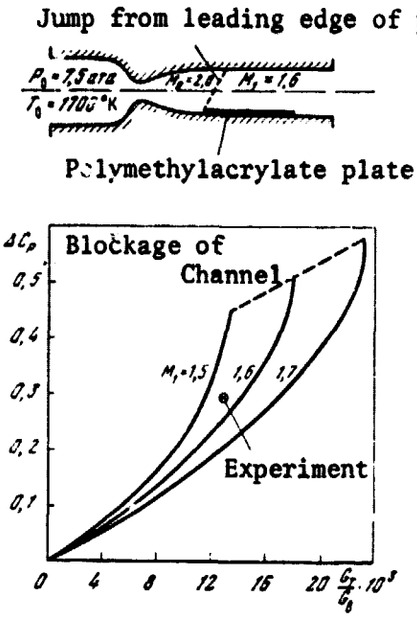


Figure 1

of flow of the supersonic stream in the channel of the hypersonic ramjet engine, qualitative estimation of the effectiveness of various rules of change of the cross section of the gas-flow channel of the hypersonic ramjet engine.

Figure 2, for illustration, shows two possible methods of placement of the fuel substance, acting simultaneously as a structural element of the flow-carrying portion of a hypersonic ramjet engine. The combination of these methods can significantly decrease the shortcomings inherent in each of the methods individually. The shortcoming of the second method is the decrease in the length of the combustion chamber and, consequently, reduction in completeness of combustion or, if the chamber is first made elongated, increase in the losses to friction.

The shortcoming of the first method is the increase in the area of the throat.

In order to avoid worsening the process of compression in the air collector and, consequently, the effectiveness of the engine as a whole, in the case of the use of the first method (see Figure 2, diagram 1), it is desirable to increase the angle of attack of the air collector as the length of the throat is increased. The flow in asymmetrical air collectors is such that as the angle of attack is increased, the cross-sectional area of the incoming stream is increased, the degree of its constriction remaining unchanged if at the same time the area of the throat is increased. The possibility is also studied of mechanical regulation of the throughput section by means of movement of the shell or a central body.

Let us first discuss the method of calculation of the characteristics of the engines in question, their parameters and forces acting on the individual structural elements.

In determining the characteristics of the engine, the following calculation model is used: the flow in the air collector and nozzle is considered two-dimensional, since in the present work only flat ramjets are considered, the flow in the combustion chamber is considered one-dimensional.

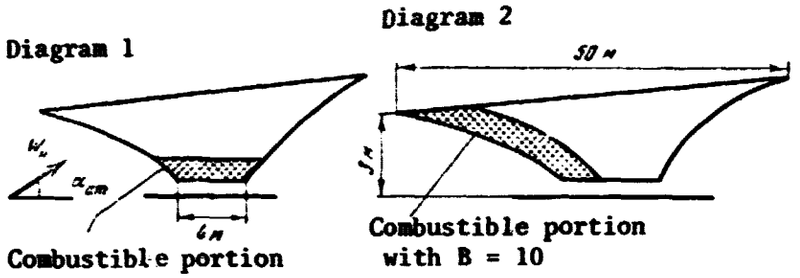


Figure 2

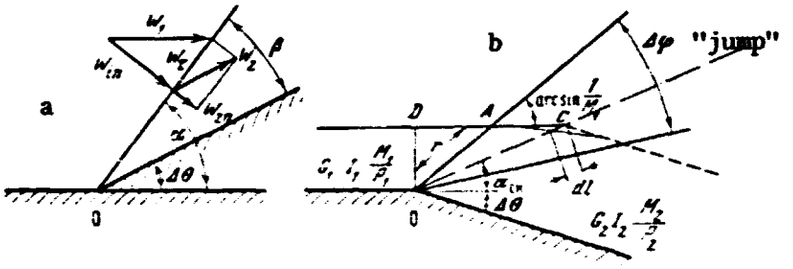


Figure 3

One foundation of the model is the fact that the basic gas-dynamic forces acting on the contour of a hypersonic ramjet engine are applied to the air collector and nozzle. Since the air collector and nozzle amount to up to 95% of the entire length of the engine, determination of the corresponding flow parameters and forces acting on these elements is most significant.

Non-one-dimensional calculation of the flow in the combustion chamber, due to the complexity of the processes occurring there, is not performed; therefore, the flow is considered one-dimensional. In the plan suggested for calculation, the parameters at the inlet to the chamber are produced by averaging the nonequilibrium flow at the end of the air collector according to the conditions of conservation of flow, momentum and energy. This method of averaging has yielded good results in the design of supersonic ramjet engines.

An economical calculation method has been developed for the design of supersonic two-dimensional geometrically complex flows of a compressible non-heat-conducting gas [4]. The use of the method of characteristics for such flows is difficult, and when dissipative methods of thorough calculation are used, a very dense grid must be used. The use of uneven grids, allowing increased density of nodes in the areas of interest to us leads to a decrease in the calculation speed, resulting from the

stability criteria. These difficulties can be eliminated by separating of certain discontinuities as boundaries of the areas and by the use of mobile grids [5]. In the method suggested, the boundaries of the corresponding areas are the shock waves, tangential discontinuities and isentropic "jumps" of rarefaction, which are produced when the Prandtl-Mayer waves are replaced by a fictitious discontinuity. The parameters at such discontinuities are calculated using finite formulas for a simple wave, while the angle is selected from the condition of conservation of flow rate before and after the rotation of the stream. This angle is determined by the formula (Figure 3) /97

$$\tan \alpha_{av} = \sin \Delta\theta / (P_1 M_1 \sqrt{R_2 T_2} / P_2 M_2 \sqrt{R_1 T_1} - \cos \Delta\theta),$$

where P is pressure; T is temperature; R is the gas constant. As the flow is rotated by an angle exceeding the assigned maximum value of $\Delta\theta_{max}$ (according to the necessary accuracy), the Prandtl-Mayer wave is replaced by a sheaf of rarefaction jumps. A similar suggestion was contained in the approximate method of calculation of hypersonic flows [6]. However, the condition of conservation of flow rate was not used and the interaction of the corresponding jumps not analyzed, since in the problems for which this method was used the secondary reflected waves could be ignored.

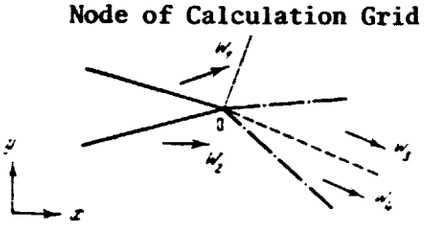


Figure 4

In the planar case, after introduction of the rarefaction jumps, the entire flow field is divided into zones with constant parameters, limited by linear jumps of any of the forms mentioned above. Calculation in this case is reduced to determination of the points of intersection of the corresponding discontinuities and parameters within such zones. Since in construction of the solution for planar supersonic flows a stationary analogue of the Cauchy problem is realized, at each point of the interaction of two discontinuities of any type one must solve the problem of the decomposition of the discontinuity of assigned intensity.

We know that the solution of this problem was used in difference plan of the method of S. K. Godunov [7-9], but the corresponding discontinuities were located at fixed points on the grid, not related to the lines of propagation of perturbations in the flow, which led to the need to calculate simple waves by a difference plan. The primary difference of the method is that the grid produced corresponds fully to the physical flow picture

and is the limiting form of the grid suggested in [5] in the case when within zones limited by weak and strong discontinuities there are no zones of the corresponding mobile grid. The thickening of the calculated points occurs in these flow areas, where there are significant gradients of the parameters. Thus, the algorithm for construction of the solution using this plan is reduced to the following (Figure 4, solid line represents previous discontinuities (known), dot-dash line -- newly formed discontinuities (calculated), dotted line -- tangential discontinuities):

1) The coordinates of the next (along x) intersection of the two discontinuities of any form are determined;

2) The problem of the decomposition of the discontinuity, determined by the flow near this point, is solved;

3) A check is made to see to what extent the parameters in the newly formed zones differ from the parameters in neighboring zones, and if this difference is less than the assigned calculation accuracy, the boundary between these zones is eliminated from analysis.

After this, the following point of the intersection is calculated.

In order to produce a nondivergent numerical plan, the convergence was demonstrated where $\Delta\theta_{max}$ approaches 0. Accuracy estimates show that as concerns the x component of the pulse, the method is a first order method, while as concerns the y component /98 it is a second order method. All calculations were performed with an integral accuracy of 2-3% as to force acting on the wall.

For the plans 1 and 2 studied (see Figure 2), we calculated the flow in a mixed compression air collector. An air collector of the same type as in [10] was studied, differing from that indicated in that the central body (c. b.) was profiled with two jumps, while in [10] there were no jumps. Figure 5a shows the distribution of temperatures and pressures on the surface of the shell (dotted line) and central body (dotted line) of the air collector in question. As we can see from the figure, a complex flow occurs in the channel with jumps which cause a multistep change in parameters on the walls of the air collector. The distributions produced are necessary for estimation of the rule of change of geometry of the channel over the length of the engine in the assigned flight mode.

The distribution of the same parameters for two cross sections in the air collector (location of cross sections shown in Figure 5, b) is shown in Figure 6a, b, and allows us to make similar estimates as a function of the flight mode (solid line is cross section x, dotted line -- section b). It should be

noted that for external stagnation air collectors, the fluctuations in pressure and temperature will be still greater due to the high angles of flow rotation; therefore, the development of engines with collectors of this type may involve greater difficulties than with mixed compression air collectors.

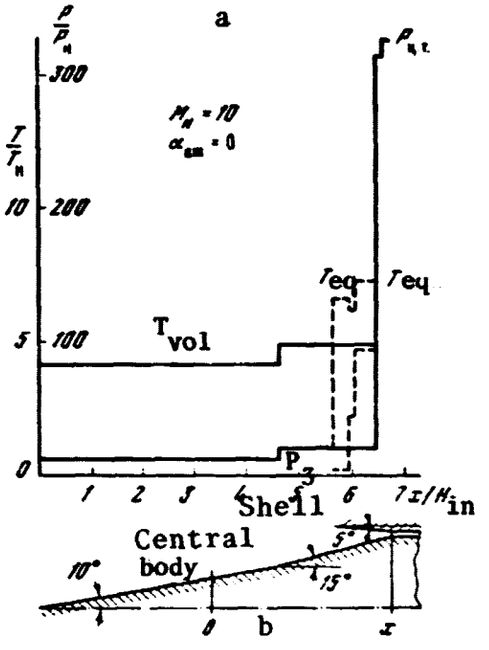


Figure 5

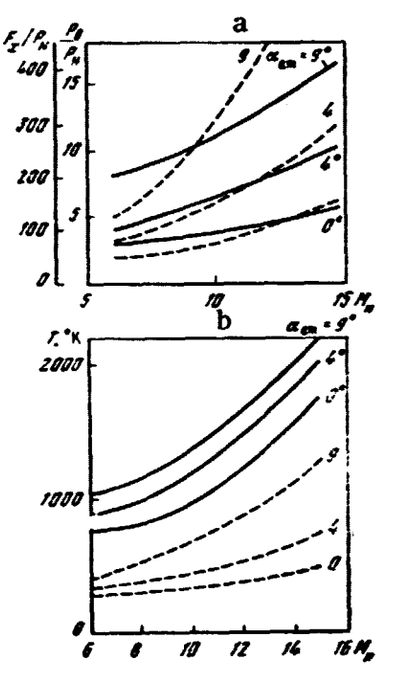


Figure 6

As was noted above, for plan 1 (see Figure 2), the increase in throat area must be compensated by an increase in angle of attack or by bringing the shell closer to the central body.

On Figure 7 for a flight vehicle (flying at a speed corresponding to $M_H = 10$), we show the relative area of the throat $F_x = F_x/F_H^1$ with an excess air factor $\alpha = 1.1$ as a function of angle of attack α_{at} as the throat is thermally eroded in flight. /99

We can see from the figure that full compensation of the thermally eroded area of the throat due to an increase in the angle of attack does not occur, since the rate of erosion is quite high (3-5 mm/sec).

For this same vehicle ($M_H = 10$), we analyzed the increase in range upon transition from a kerosene ramjet to a beryllium ramjet according to plans 1 and 2.

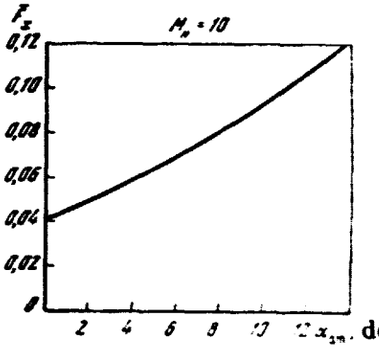


Figure 7

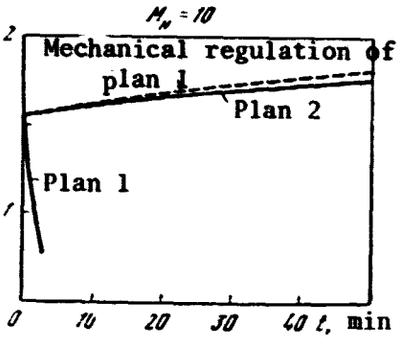


Figure 8

In this case, we assumed constancy of the quality of the flight vehicle and assumed that the weight of the beryllium was equal to the sum of the weights of the kerosene, the system required to feed it and the thermally insulated tanks (it was considered that the weight of the tanks and fuel feed system for kerosene amounted to 5% of the launch weight of the entire vehicle, the total fuel weight -- 30%, corresponding to the data used in [11]).

The main dimensions of the apparatus necessary to estimate the thermal erosion are presented in Figure 2. The increase in range indicated is: $\bar{L} = L_{Be}/L_k = J_k \ln (G_0/G)_{av}/J_k \ln (G_0/G)_k$, where Be is beryllium; k is kerosene; L is the range of flight of the vehicle; J is the specific impulse of the ramjet engine; G_0 is the launch weight of the vehicle; av is the mean value during the time of the flight; G is the final weight of the vehicle.

The results of the corresponding calculations are presented in Figure 8. Obviously, plan 1 should be used only with brief flight times, i.e., for acceleration devices, while plan 2 is effective over a broader range of flight times. With mechanization of the shell, plan 1 allows even somewhat greater increase in range than plan 2. This occurs due to the improvement of the characteristics of the hypersonic ramjet, since the flow-carrying portion in plan 1 can be made shorter and the characteristics of the engine (J_{Be}) will be better.

The analysis performed indicates that the use of plan 2 with atomization of Be allows a significant increase in flight range (by an average of 1.6 times) in comparison with a kerosene-burning ramjet. Furthermore, the use of beryllium allows a significant decrease in the drag of the vehicle due to a decrease in dimensions, since the specific weight of beryllium is

[1]Here F_H is the area of the inlet stream; F_x is the area of the throat.

approximately double that of kerosene. By increasing the thrust, /100
the maximum cross section of the apparatus can be decreased by a factor of approximately 2.5.

Thus, we can see from the above that the idea of F. A. Tsander of the possibility of using structural elements of a flight vehicle as fuel may be realized in the planning of hypersonic ramjet engines.

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THE INFLUENCE OF SHIELD PARAMETERS ON ESTIMATION OF THE EFFECTIVENESS OF A SOLAR SAIL

I. A. Merkulov and I. A. Khoromskiy

Among the many ideas set forth by F. A. Tsander, our attention is drawn by the suggestion to use the force of light pressure to move space vehicles [1]. Many scientists have developed this idea of Tsander [2-7] and studied the possibility of using a solar sail both as a power plant and as an element of the orientation system. The solar sail, doubtless, has the advantage of simplicity in comparison to other types of power plants, and this property, possibly, will allow it in the future to be practically used in space vehicles. In evaluating the effectiveness of the use of a solar sail, there is doubtless interest in analysis of its weight indicators and comparison of these indicators with the weight indicators of other types of power plants. Earlier, the question was studied of comparison of the weight characteristics of a solar sail and an ion engine, developing the identical thrust. The source of energy in both cases was a solar /101
shield, but in the first case it was a sail, in the second case -- a solar battery supplying electric power to the ion engine.

In the present work, we have set ourselves the task of determining the influence of the parameters of the two types of solar shield on the advantages in the weight aspect of the solar sail or ion power plant, creating identical thrust. As parameters determining the result of the comparative weight estimate, we used the weight of 1 m^2 of the sail (γ_s) and the battery (γ_b), the efficiency of the solar battery (η_b) and the sail (η_s), the ratio of the projection across the direction of the acceleration vector of the effective pressure experienced by the sail to the maximum theoretical value of force of the sail.

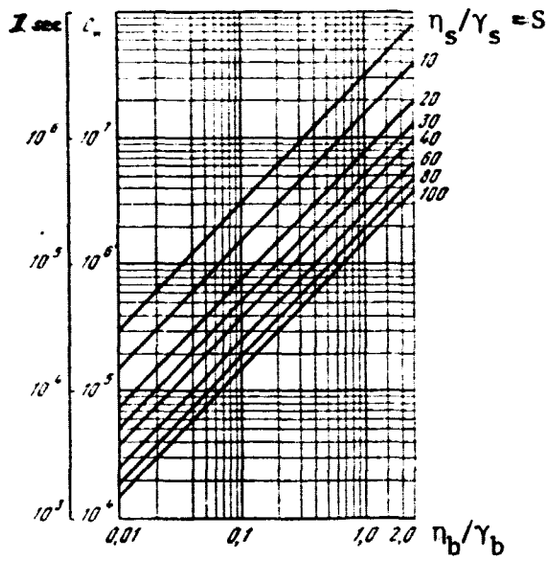


Figure 1

In performing our comparative estimation of the solar sail and the ion power plant, we analyzed the change in parameters within the ranges $5 \leq \eta_s/\gamma_s \leq 100$ and $0.01 \leq \eta_b/\gamma_b \leq 2$.

Figure 1 shows the values of these parameters as they influence the optimal specific impulse of the ion engine and

the mass coefficient of the relationship of power and pressure of the solar shield.

The optimal value of impulse of the ion engine, providing the maximum operating time, for which the mass of the solar battery with reserves of working fluid for the engine does not exceed the mass of the solar sail, is

$$J = 1.53 \cdot 10^7 \frac{\eta_b \gamma_s}{\eta_s \gamma_b}.$$

The mass coefficient of the ratio of power (N_b) and pressure (P_s) of the solar shield is determined by the formula

$$C_M = \frac{1.5 \cdot 10^8 \eta_b \gamma_s}{\eta_s \gamma_b} \text{ [kgm/kgs]}.$$

As was shown in [8], where $C_M \geq 10^5$, the ion engine, supplied by the solar battery, with a store of working fluid, has an advantage in weight over the solar sail if the operating time is over 10,000 hr. Figure 1 allows us to determine the values of the parameters of the solar shields for which this condition is realized. As we can see from the figure, where $\eta_b/\gamma_b > 0.07$ (for example, $\eta_b = 0.07$ and $\gamma_b = 1$ kg/m^2), for all of the values of the parameters of the sail studied, including $\eta_s/\gamma_s = 100$ (for example, $\eta_s = 0.5$ and $\gamma_s = 0.005$ kg/m^2), the value of $C_M > 10^5$. With inferior values of the parameters of the solar battery, i.e., where $\eta_b/\gamma_b \ll 0.07$, the question of the advantage /102 in the weight respect of one power plant or the other depends on the possible parameters of the solar sail. For example, where $\eta_b/\gamma_b = 0.02$ ($\eta_b = 0.06$; $\gamma_b = 3$ kg/m^2), the solar sail is inferior in the weight respect to the ion power plant only if it has high specific weight $\gamma_s > 0.015$ kg/m^2 (where $\eta_s \approx 0.5$). With a lower specific weight of the solar sail or with a higher value of thrust factor, the sail is lighter than the ion power plant with fuel reserve for long operating times ($\tau > 10{,}000$ hr). In this case, the equality of the weights of the power plants will occur with significantly shorter flight durations.

Figures 2-4 show how the parameters of the shields of the solar sail and solar battery influence the time of functioning of the installation for which their weight, including the weight

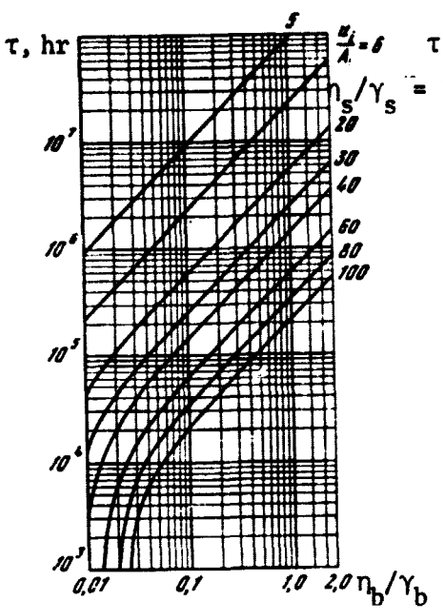


Figure 2

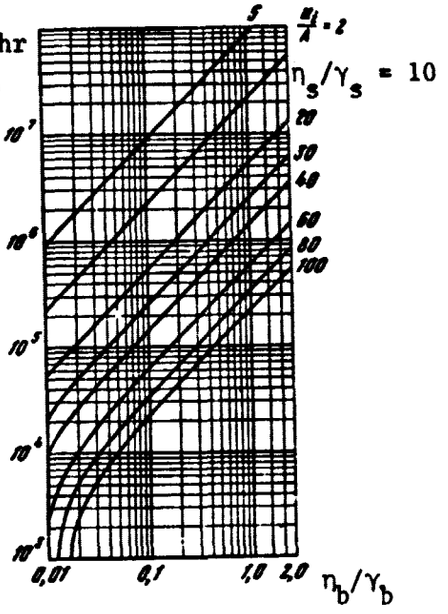


Figure 3

of fuel, is identical. This time can be arbitrarily called the time of equal weights of power plants. The desired value of this time is determined by the formula

$$\tau = [2.28 \cdot 10^9 (\frac{\eta_b \gamma_s}{\eta_s \gamma_b})^2 - 19.5 \frac{U_i}{A}] \frac{\gamma_b}{\eta_b} \quad [\text{hrs}].$$

In determining this time for the impulse of the ion engine we used the optimal value, realizing the maximum time.

The time of equal weights of power plants limits the area in which the advantage in the weight respect belongs to one or the other of the two types. With a working time less than that given by the formula presented, the ion power plant is lighter, while with a greater duration, the advantage in the weight respect belongs to the solar sail.

The weight of the ion power plant depends on the expenditures of energy for ionization of the working fluid. The greater these expenditures, i.e., the greater the value of U_i ("cost" of an ion), the greater the energy which must be fed to the device to supply the engine, maintaining its thrust equal to the force of the sail. Correspondingly, the power and weight of the /103

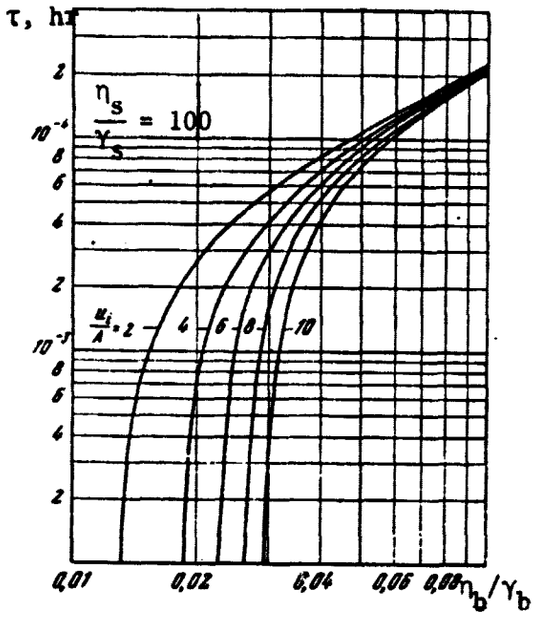


Figure 4

solar battery increase. Therefore, the graphs are constructed for two values of ratio of U_i to the atomic weight of the working fluid: $U_i/A = 2$ and 6.

With high values of the parameters of the solar sail ($\eta_s/\gamma_s \geq 80$) and low values of the parameters of the solar battery ($\eta_b/\gamma_b < 0.02$), the ion engine, supplied by a solar battery, is heavier than the solar sail with operating times of less than 1000 hours. However, if we improve the parameters of the solar battery, raising them to $\eta_b/\gamma_b = 0.1$ and assume $\eta_s/\gamma_s = 40$, the ion power plant is lighter than the solar sail, even if it carries reserves of working fluid for 100,000 hours of operation. We note that the relationship of parameters of solar shields of the two types analyzed in this example corresponds to the case when the value of η_s is 10 times greater than the value of η_b, while the specific weight of the solar battery is 40 times greater than the specific weight of the solar sail.

As Figures 3 and 4 show, the increase in expenditure of energy for ionization decreases the functioning time of the ion power plant for which its weight with the weight of the reserves of working fluid is equal to the weight of the solar sail. For example, when $\eta_s/\gamma_s = 80$ and $\eta_b/\gamma_b = 0.02$ where $U_i/A = 2$, the time of equal weights is over 5000 hours, where $U_i/A = 6$ it is reduced to about 1000 hours. Thus, a three-times increase in expenditures of energy for ionization reduces the time of equal weights of comparable installations by a factor of 5. However, this great reduction in time of equal weights due to the increase in the expenditures of energy for ionization is observed only in the areas of low parameters of the solar battery and high values of the parameters of the solar sail. This is the area in which the solar sail is competitive in the weight respect with the ionic power plant. As the parameters of the solar battery improve, the influence of the expenditures of energy on ionization for a comparative estimation of the ionic installation and the solar sail decrease. Thus, where $\eta_b/\gamma_b \geq 0.1$, with all of the values of parameter η_s/γ_s presented in the graphs the

influence of the value of U_i is negligible. The same occurs when the parameters of the solar sail become worse. For example, where $\eta_s/\gamma_s \leq 10$, for all of the values of parameter η_b/γ_b presented on the graph, the expenditures of energy for ionization have practically no influence on the duration of operation corresponding to the time of equal weights of the installation. Consequently, in the area of values of parameters of shields where the ionic /104
installation with its reserves of working fluid is lighter than the solar sail with a time of operation equal to 10^5-10^6 hr, the influence of the expenditures of energy for ionization of the working fluid is very slight, and in practice this influence can be ignored. This result is quite understandable. As the duration of operation of an ion engine increases, the optimal value of the specific impulse increases. But with a high specific impulse, i.e., with high consumption of power for acceleration of ions, the expenditures of energy for ionization represent a slight fraction in the total consumption of energy to supply the engine and their influence on the comparative evaluation of the power plants is very slight.

The graphs studied indicate that with relatively high parameters of the solar battery, characterized by $\eta_b/\gamma_b \geq 0.1$, with wide variations in consumption for ionization of the working fluid, the ion power plant with reserves of working fluid has an advantage in the weight respect over a solar sail with flight durations of up to 20,000 hours. This conclusion is correct for any of the values of parameters of the solar sail studied, including the highest -- $\eta_s/\gamma_s = 100$. Therefore, the comparative evaluation of the solar sail and ion power plant as to weight indicators should be performed only for relatively low parameters of the solar battery, i.e., where $\eta_b/\gamma_b < 0.1$. In this area, the conclusion concerning the advantage of one power plant or the other cannot be unambiguous. Therefore, this area of parameters of the solar battery is worthy of most detailed analysis. Based on these considerations, on Figure 4 the time of equal weights is shown for the area $0.01 \leq \eta_b/\gamma_b \leq 0.1$, where we clearly see how the expenditures of energy for ionization influence the comparative evaluation of the two installations. We note that with low parameters of the solar sail ($\eta_s/\gamma_s = 10$), even in this area of relatively low values of parameters of the solar battery, the advantage in weight is retained by the ion power plant with τ up to 200,000 hours. This statement is correct for any values of consumption of power for ionization within the range $0 \leq U_i/A \leq 10$.

With the middle range of the analyzed values of parameters of the solar sail, $\eta_s/\gamma_s = 40$, the weight advantage of the ion installation (where $\tau \geq 20{,}000$ hr) does not exist with all values

of the parameter η_b/γ_b and the consumption of power for ionization has a great influence. For example, where $\eta_b/\gamma_b = 0.01$, where $U_i/A = 2$, the time of equal weights of the installations compared is 10,000 hr, where $U_i/A = 6$ it drops to 2500 hr, while where $U_i/A = 8$ it is much less than 1000 hours. The influence of the parameters of the solar battery and the power consumption for ionization has a still greater effect on the comparative weight evaluation of the two installations with high parameters of the solar sail (see Figure 4).

Analysis of this last graph indicates that with high values of the parameters of the solar sail, characterized by $\eta_s/\gamma_s = 100$, and low values of parameters of the solar battery, characterized by $\eta_b/\gamma_b \leq 0.05$ where $\tau = 10^4$ hr, the solar sail has an advantage in the weight respect over the ionic power installation. The graph also shows how the parameters of the solar battery and consumption of power for ionization of the working fluid influence the time of operation of the installation, for which a transition from the ionic installation to a solar sail is advantageous.

The study performed into the influence of the parameters of the solar shield of each type on the comparative weight evaluation of the solar sail and the solar battery feeding the ion engine have allowed us to establish precisely the areas of these parameters where the solar sail has the advantage and where it is inferior to an ion power plant. The graphs presented in the work allow us, using the known values of parameters of the solar sail η_s/γ_s and the solar battery η_b/γ_b, as well as the known value of energy cost of ionization of the working fluid in the ion engine U_i/A, to establish the functioning time of power plants for which the advantage in the weight respect goes over from the ion installation to the solar sail. /105

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THE THEORY OF THE GAS THERMAL COMPRESSOR

R. I. Kurziner, A. N. Knyazev and I. V. Zakharov

One means for improving the effectiveness of the cycle of reaction of reaction engines which has been rather broadly used in recent times is to increase the elevation in pressure achieved in turbojet engines by increasing the total pressure rise in the compressor π_k^*, and in a ramjet engine by increasing the rise in air pressure as a result of dynamic compression due to the velocity head π_v^* while simultaneously increasing the maximum temperature of the cycle.

Studying the possibility of improving the thermodynamic cycle of jet engines, F. A. Tsander in his work "The Problem of Flight by Means of Reaction Apparatus" analyzed another interesting method of increasing the pressure of the cycle, namely increasing the degree of elevation of pressure as a result of heat liberation from the gas stream. In particular, he suggested hyperexpansion of the stream of combustion products leaving the reaction engine to a pressure below atmospheric pressure, followed by compression of the stream using the heat liberated from the stream [1]. The realization of such a cycle with regeneration of the heat by fuel represents certain possibilities for improving the thermal efficiency. /106

If we eliminate from analysis the system required to cool the gas stream, based on the principle of collection of energy (turbine expansion engines) or mass (for example a vortex flow separator), the physical means of cooling the stream amount to two: 1) heat liberation from the stream through the walls of the channel; and 2) feeding a liquid into the gas stream, leading to its intensive cooling due to evaporation of the liquid or an endothermic reaction of the liquid with the stream.

In a work by R. I. Kurziner, V. I. Kirillov, F. V. Koroleva and V. I. Shcherbakov [3], reported at the First Readings Dedicated to the Development of the Scientific Heritage and Ideas of F. A. Tsander, it was noted that with heat transfer to the walls of the channel, it is impossible to achieve an increase in total pressure of the stream. This is not difficult to show using the following equation for a flow with heat input or output in a cylindrical channel considering friction, calculated on the assumption of applicability of the basic regularities of the hydrodynamic theory of heat exchange:

$$d \ln P^* = \frac{kM^2}{2} \frac{T^* - T_w}{T^* - T_w} d \ln T, \qquad (1)$$

where P* and T* are the full pressure and temperature of the stream; T_w is the temperature of the wall; M is the M number of the stream; k is the mean adiabatic index of the gas.

In analyzing the equation presented, it is not difficult to reach the conclusion that both with heat input, when d ln T > 0, while T* < T_w, and with heat output, when d ln T < 0 while T* > > T_w, the full pressure of the gas stream drops. It can be shown that the heat liberated from the gas stream can only decrease the losses of total pressure resulting from friction of the gas on the wall of the channel. The total pressure of the gas stream can be increased by feeding into it liquids which intensively absorb heat due to evaporation or endothermic reaction. For a preliminary analysis of this effect, it is convenient to utilize the generalized equation of the interaction, produced by joint solution of the main equations of conservation (continuity, momentum and energy) for the one-dimensional flow of an ideal gas:

$$d\ln P^* = -\frac{kM^2}{2}\left[d\ln T^* + 4f\frac{dx}{d_{eq}} + 2(1-y)\,d\ln G - d\ln\mu\right], \qquad (2)$$

where f is the coefficient of surface friction; d_{eq} is the equivalent diameter of the channel; $y = v_w/V_{stream}$ is the relative velocity of the substance fed in; G is the mass flow rate of gas per second; μ is the molecular weight.

We can see that the full pressure of the gas stream is decreased due to friction against the wall of the channel, aerodynamic drag resulting from injection of the liquid ($y = v_w/V_{stream} < 1$) and the decrease in molecular weight, but increases upon heat liberation (d ln T* < 0). It is characteristic that the influence of all of these actions, including heat liberation from the stream, is a result of the dynamic process of interaction of the proportionality of changes of total pressure to the square of the number M and is not related to thermodynamic changes in the static system. Thus, a preliminary analysis shows that in order to produce significant changes in total pressure, we must feed the additional liquid at high subsonic or supersonic speeds of the gas stream. Furthermore, it is not difficult to see that the term in equation (2) considering the friction of the gas against the wall is independent of the degree of cooling of the stream, but rather is primarily a function of the rate of occurrence of the reaction. In other words, assuming that the reaction occurs instantaneously or that the channel has sufficiently great diameter d_{eq}, we can simplify

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equation (2), excluding the term considering the friction of the gas against the wall of the channel.

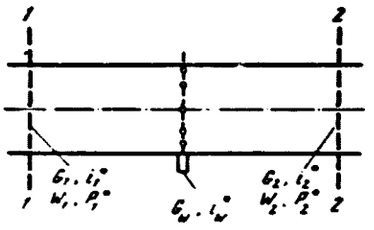


Figure 1

Let us also assume that the liquid is sprayed into the channel at a negligible velocity (or, which is similar, perpendicular to the gas stream). Then the calculation plan for the flow is represented as shown in Figure 1.

For these conditions, equation (2) takes on the following form (for example, see [2]):

$$d\ln P^* = -\frac{kM^2}{2}[d\ln T^* + 2d\ln G - d\ln \mu]. \quad (3)$$

For the flow with k = const, we can express the change in full pressure as a function of the relative change in gas flow rate and its heat content as the liquid is sprayed in by the equation

$$d\ln P^* = -\frac{kM^2}{2} d\ln (i^* G^2), \quad (4)$$

where i* is the heat content of the gas in an arbitrary cross section of the channel.

We can see that only in the case of decreasing enthalpy can introduction of matter to the gas stream lead to an increase in its total pressure. Since with introduction of additional matter the gas stream undergoes two simultaneous effects -- application of the mass and a change in the physical or physical and chemical composition as a result of evaporation and the interaction, the selection of matter to achieve the maximum increase in pressure must be made so that the process of heat absorption, characterized by a decrease in the temperature of the stream, dominates over the process of increasing mass, i.e., the following condition is satisfied:

$$d\ln(i^* G^2) \leqslant 0. \quad (5)$$

In the simplest case, when an evaporating liquid is sprayed into the stream of heated gas, equation (5) can be reduced to

the form

$$r + i_w^{*T_{ev}} - i_w^* - i_r^{*T_{ev}} - \frac{1}{1-d_w} i_1^* > 0, \qquad (6)$$

where r is the latent heat of evaporation of the liquid; $i_w^{*T_{ev}}$, $i_r^{*T_{ev}}$ are the heat contents of the liquid and vapor at the evaporation temperature; i_w^* is the heat content of the liquid injected; $d_w = G_w/G_1$ is the relative flow rate of the liquid sprayed in.

Among the substances satisfying the requirements presented over a broad range of change of the initial heat content of the gas stream (including at high values of i_1^*, we can think of both chemically inert (water and other) and chemically active substances, entering into endothermic reactions with the gas stream at atmospheric pressure (see table).

We can see that in most of the substances presented, the total thermal effect of heat absorption is quite great. At low values of gas stream temperature, the endothermic reactions do not occur and therefore under these conditions the use of the latent heat of evaporation is of greatest interest from the standpoint of achieving the maximum increase in total pressure of the stream. /108

Characteristics	H_2	CH_4	CH_3OH	C_2H_5OH	NH_3	H_2O
Latent heat of evaporation, kj/kgK	457	515	1210	930	1332	2250
Heat of endothermic decomp. react., kj/kgK	—	4690	7440	6020	2722	13450
Total thermal effect, kj/kgK	457	5205	8650	6950	4054	15700

We can see from the table that in this case, water is the ideal liquid for its use in a gas thermal compressor. Thus, in [2] it was experimentally demonstrated that even at moderate velocities at the inlet ($M_1 \approx 0.8$) with an increase in the relative quantity of water sprayed in $d_{H_2O} = 0.3$, we can increase the total pressure of the gas stream by 15%, producing π_{com} comparable to the degree of increase in pressure in the low-pressure stage of a subsonic compressor.

As an example of the use of the chemical reaction of decomposition of the substance sprayed in, we have calculated the parameters of a high temperature inert gas stream when ammonia is sprayed in. The calculations were performed using an approximate method on the assumption of constant adiabatic index k and the assumptions presented earlier (flow in a cylindrical channel without friction with injection perpendicular to the stream).

It is shown that the heat liberation from the gas achieved by injecting ammonia into the stream leads to an increase in the compression ratio $\pi_{com} = P_2^*/P_1^*$ and the throughput capacity of the channel $\omega = (G_{2max} - G_w)/G_{1max}$, characterized by the maximum flow rate of the working fluid through an assigned cross section which is greater, the greater the value of the adjusted velocity and the lower the heat content of the gas at the inlet. When successive alternation of cooling of the stream (as a result of evaporation of NH_3 and its decomposition into hydrogen and nitrogen) and deceleration of the cooled stream without losses is used, in the limiting case the total pressure can be increased in the range of 1.0 to 2.5 times as a function of the parameters of the stream and the values of d_{NH_3}. We note that under actual conditions, due to the finite nature of the mixing time and the reaction, and also the influence of losses of total pressure in jumps (in the version with successive cooling and deceleration of the stream) and to friction, which has a significant influence with high values of stream velocity w_1, low values of d_{eq} and low values of i_1^*, we can expect a significant drop in the useful effect.

There is significant practical interest in substances which enter into endothermic reactions with the combustion products. These substances must include methane, which enters an endothermic reaction with water present in the combustion products of any hydrogen-containing fuel (conversion reaction). Each kilogram of methane entering into the reaction absorbs from 10,450 kj/kgK (in comparison to 2250 kj/kgK upon evaporation of water). The use of the interaction of methane with water is even more attractive, since the final products contain hydrogen and therefore can be used as a high-calorie fuel. /109

Due to the fact that this reaction involves a significant change in the composition of the gas mixture, determination of the parameters of the thermal compressor requires calculation using the equilibrium equations. In this case, the calculation is significantly complicated and can practically be performed only using a computer. In the present work, we used a standard program for equilibrium thermodynamic calculation. The ordinary assumptions were made: flow in a cylindrical channel without

friction, injection of methane perpendicular to the main stream, and chemical reactions occur instantaneously.

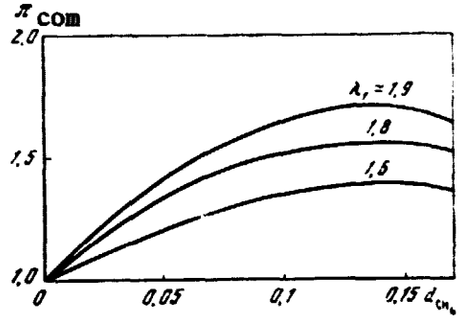


Figure 2

The calculation model of the thermal compressor included a hydrogen-air combustion chamber burning a mixture with α = 1.0, a Laval nozzle in which the gas stream is accelerated to high velocity, and a cylindrical chamber with a methane feed zone, where the endothermic reaction of conversion occurs. The calculations were performed with various degrees of expansion of the gas in the nozzle (various λ_1) and various quantities of fluid injected. The results of the calculations are presented in Figure 2. As was to be expected, the degree of increase in pressure has its optimal value for a certain quantity of liquid injected. The value of π_{com} increases with increasing speed at the inlet to the thermal compressor and relative quantity of injected methane, reaching, where λ_1 = 1.9, d_{CH_4} = 0.12, a value of π_{com} = 1.7 and, then, with increasing d_{CH_4}, beginning to decrease, since with values of d_{CH_4} greater than 0.12-0.15 the effect of mass input will become more significant than the heat liberation from the stream due to the chemical interaction.

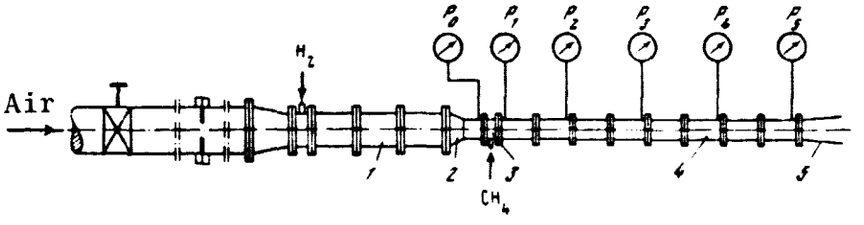


Figure 3

In order to evaluate the trends revealed, experimental work was performed using a hydrogen-air combustion chamber available to the authors with a mass flow rate G_r = 0.25-0.3 kg/sec, pressure P_r^* = 3-4 kg/cm^2 and α_ε = 0.91-0.98.

The plan of performance of the experiments, showing the cross sections of injection and the points of measurement of the static pressure, is shown in Figure 3. The diameter of the channel of the gas thermal compressor d = 55 mm, the length of all cross sections is 1000 to 2000 mm. /110

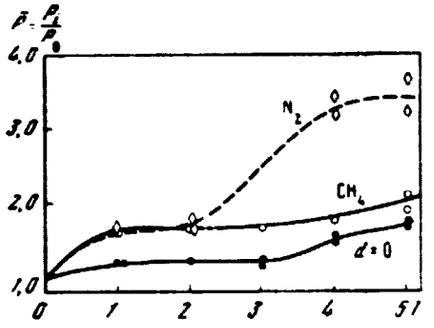


Figure 4

The influence of mass input and friction, which plays a rather significant role at the high velocities of the gas stream and low channel diameter used, was estimated from the results of experiments with injection of inert N_2 into the gas stream.

The results of experiments, in the form of dependences of relative pressure over the length of the channel (ratio of pressures P_i/P_0) on length, are presented in Figure 4. We can see that due to the influence of friction, the static pressure over the length of the channel increases by approximately 1.5 times. When inert nitrogen is injected at $d_{N_2} = 0.093$, due to the total effect of mass input and friction the static pressure increases by a factor of 3.5. When methane is injected to the stream at the same value of d_{CH_4}, the static pressure in the output cross section of the channel increases significantly more slowly, exceeding the static pressure of the gas stream without supplying additional matter by only 20-30%. This result indicates the occurrence of an endothermic reaction upon injection of methane into the combustion products.

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IGNITION AND COMBUSTION OF METAL PARTICLES

L. A. Klyachko

The idea of the use of metals as a component of rocket fuels belongs to F. A. Tsander and was first stated by him in 1909. Subsequently, F. A. Tsander developed this idea in works published in 1936-1937 [1, 2].

At the present time, the ideas of F. A. Tsander concerning the use of light metals have been put into practice: the composition of a number of fuels for rocket engines includes aluminum and magnesium, and the possibility is being studied of using beryllium and lithium. In developing such fuels, the need has naturally arisen to study the regularities of ignition and combustion of individual particles of various metals and their gas suspensions. The results of the investigation of these problems are analyzed in the present work, though we do not claim exhaustive coverage of the problem. /111

The peculiarities of ignition and combustion of metals are determined primarily by the presence on the surface of the particles of an oxide film, by their high combustion temperature and by the formation in most cases of solid reaction products.

The metals can be classified as a function of the nature of their ignition and combustion. In the process of ignition of metals, a decisive role is played by the diffusion permeability of the oxide film, as well as the solubility of the oxidizer and the oxide in the metal itself. The nature of combustion of the metals is determined by the relationship between the combustion temperature and the boiling point of the metal. Radiation heat transfer from the combustion zone is of great significance in this case.

The specifics of the reaction of oxidation of metals include the fact that the reaction rate depends not only on the temperature and concentration of the oxidizer (as for ordinary heterogeneous reactions), but also on the thickness of the oxide film. The phenomenological rule of oxidation of metals can be represented as [3]

$$\frac{d\delta}{d\tau} = f(\delta) k_{\text{п}} C_{\text{ок}}^{m} e^{-\frac{E}{RT}}, \qquad (1)$$

where δ is the thickness of the oxide film; k_{π} is the preexponential factor; C_{ok} is the concentration of oxidizer at the surface of the metal; E is the activation energy; T is the temperature.

For the so-called exponential rules of oxidation

$$f(\delta) = \delta^{-n}. \tag{1a}$$

Where n = 0 (linear oxidation rule), the reaction rate is independent of the thickness of the film and the ignition of metal particles is described by the ordinary regularities of heterogeneous ignition. This mechanism is characteristic for magnesium and lithium.

Where n = 1, 2, etc. (parabolic, cubic, etc. rules of oxidation), ignition of metal particles is determined by the relationship between the rate of heat liberation (under conditions such that the thickness of the film in the preignition period increases) and the rate of heat liberation into the surrounding medium.

The process of ignition is described by equation (1) and by the thermal balance equation

$$Cm\frac{dT}{d\tau} = S\left[Qf(\delta)k_0C_{ox}^m e^{-\frac{E}{RT}} - \alpha(T - T_\infty)\right], \tag{2}$$

where C is the heat capacity of the metal, m is the mass; S is the surface area of a particle; Q is the thermal effect of the reaction; α is the heat transfer coefficient; T_∞ is the ambient temperature.

Equation system (1)-(2) was studied in [4] in order to determine the critical conditions of ignition, and in particular the dependence of ignition temperature on particle diameter.

Analysis has shown that the form of the solution of system (1)-(2) depends basically on the values of two parameters: /112

$$\Omega = \left(\frac{3QE}{CRT_0^2}\right)^{n+1}\frac{C_2}{3\lambda}\frac{k_0C_{ox}^m}{r_0^{n-1}}\exp\left(-\frac{E}{RT_0}\right); \tag{3}$$

$$\gamma = \frac{r_0}{3\delta_H}\frac{CRT_0^2}{EQ}, \tag{3a}$$

where ρ is the density; r_0 is the initial radius of a particle; λ is the heat conductivity coefficient of the medium; δ_H is the initial thickness of the oxide film.

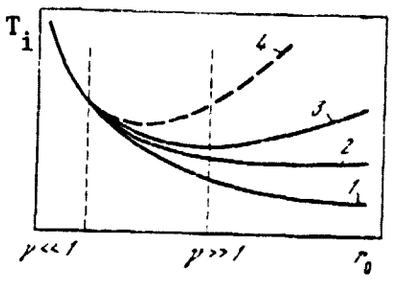


Figure 1. Ignition Temperature as a Function of Particle Radius for Various Rules of Oxidation. 1, n = 0 -- Linear Rule (Heterogeneous Reaction); 2, n = 1 -- Parabolic Rule; 3, n = 2 -- Cubic Rule; 4, n >> 1

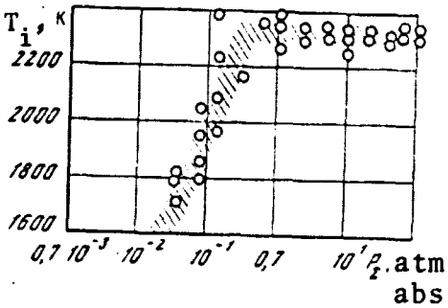


Figure 2. Ignition Temperature of Aluminum Wire as a Function of Ambient Pressure

Near the critical value, slight changes in the parameter Ω, similar to the well-known parameter of D. A. Frank-Kamenetskiy, leads to a significant change in the nature of the dependence of particle temperature on time: with values of Ω less than the critical value, the temperature of a particle first increases slightly as time passes, then decreases (the particle does not ignite); if Ω exceeds the critical value, the particle ignites.

Figure 1 shows the qualitative dependences of ignition temperature on particle diameter for various rules of oxidation (with identical initial thickness of the oxide film). As we can see, where $n > 1$, $T_i = f(r_0)$ is nonmonotonic in nature.

The reason for this nature of the dependence is as follows. In contrast to the ordinary heterogeneous reaction ($n = 0$) as a protective oxide film is formed on the surface of the metal particle, the rate of heat liberation decreases with increasing thickness. Since as the particle size increases, its heating time increases, when the rate of oxidation is strongly dependent on film thickness ($n > 1$), the decrease in the rate of heat liberation predominates, causing an increase in film thickness in comparison to the decrease in the intensity of heat liberation ($\alpha = \lambda/r_0$), and the ignition temperature increases. For small particles, their heating time is slight, the thickness of the film changes but slightly during the preignition period, and the dependence $T_i = f(r_0)$ approximates the usual dependence for the case of a heterogeneous reaction (area of small values of γ).

In [5], a similar problem was solved for the so-called direct logarithmic rule of oxidation ($f(\delta) = e^{-\delta/\delta^*}$, where δ^* is a constant).

The mechanism of ignition which we are analyzing is characteristic for metals covered with an oxide film, having protective properties (for example aluminum and beryllium). /113

However, if in the process of preignition heating the temperature of a particle reaches the melting point of the oxide, another mechanism of ignition occurs, involving a sharp drop in the diffusion resistance of the film as it melts. In this case, the ignition point is close to the melting point of the oxide and depends little on the composition of the oxidizing medium [6]. Finally, as the pressure of the medium decreases, it may occur that the boiling point of the metal itself becomes lower than the melting point of its oxide. Under these conditions, the vapors of the boiling metal penetrate through the film and come in contact with the oxidizer, which leads to ignition of the metal particle and a drop in the ignition temperature as the pressure decreases [7].

Figure 2 shows the experimental dependence of ignition temperature of aluminum wire on ambient pressure produced in [7], confirming what we have said.

For a set (gas suspension) of particles, as the author of the present report has demonstrated [8], the conditions of their ignition are significantly improved. The fact is that the liberation of the heat which is formed during the reaction on the surface of an individual particle into the surrounding medium does not change the temperature "at infinity," whereas for a set of particles, the liberation of heat from their surface does cause an increase in the temperature of the medium and, consequently, facilitates ignition of each particle.

A drop in ignition point of a gas suspension of magnesium particles with increasing concentration of the particles was discovered in [9]. Let us recall that the oxidation of magnesium is described by a linear rule, i.e., the reaction rate is independent of the thickness of the film.

For a set of particles with a heterogeneous reaction on their surface, it has been found that there are two types of ignition limits: that based on heat transfer from the entire gas suspension to the surrounding envelope and that based on consumption of the particles [10, 11].

This last type of ignition limit is specific for a gas suspension of particles and has no analogue in other combustion processes. The physical sense of the critical conditions as concerns consumption is as follows: in order for the ignition to occur in a set of particles (speaking now of a singly dispersed set), the ignition point of an individual particle, included in the set, must be reached. The critical conditions arise when even with full consumption of the particles, this temperature is still not reached.

The critical conditions of ignition of a gas suspension of particles as related to heat liberation, as was shown in [10], have the same form as for an individual particle if in place of the heat transfer factor of an individual particle α we introduce the effective heat transfer factor

$$\alpha_{ef} = \frac{\alpha}{1+A}, \tag{4}$$

where

$$A \approx \frac{3}{2\rho_p} \frac{B}{1-B} \frac{Nu_p}{Nu} \left(\frac{L}{r}\right)^2.$$

Here ρ and ρ_p are the densities of the gas and the particle; B is the mass concentration of particles; Nu_p, Nu are the Nusselt criteria for particles and the entire gas suspension respectively; L is the characteristic dimension of the system; r is the radius of a particle.

It follows from expression (4) that with a decrease in the diameter of the particles included in the set, the effective heat transfer factor first increases, then, after passing through a maximum, decreases. The ignition temperature of the gas suspension changes similarly. /114

Figure 3 shows the experimental dependence of the ignition temperature of an air suspension of magnesium particles on their diameter with a constant concentration of particles [9]. Here also, by the dotted line, we show the qualitative nature of these dependences at the limits of ignition based on consumption (curve a) and heat liberation (curve b).

As we see, the set of critical conditions for ignition of a gas suspension based on consumption and external heat transfer makes it possible to explain the extremal dependence of the ignition temperature of the gas suspension of magnesium particles on their diameter determined experimentally.

Recently, [12] appeared, in which the question of the limits of ignition of a gas suspension of metal particles was studied as applicable to the case when the metallic particles in the process of oxidation are covered by a film having protective properties (for example, aluminum particles), i.e., the reaction rate depends on the thickness of the oxide film.

The nature of the process of combustion of metal particles following their ignition depends on the relationship between the combustion temperature and the boiling point of the metal.

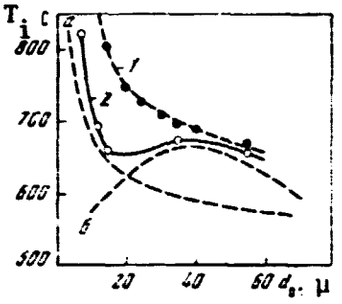


Figure 3. Ignition Temperature of an Air Suspension of Magnesium Particles as a Function of Diameter. 1, Individual Particle; 2, Gas Suspension (Concentration 60 mg/ℓ); a, Consumption Limit of Ignition; b, Heat Transfer Limit of Ignition

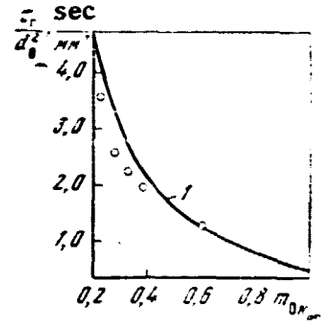


Figure 4. Relative Combustion Time of Aluminum Particles as a Function of Molar Share of Oxygen in the Surrounding Medium (d_0 = 60 μ, T_∞ = 2500 K). o, Experimental Point; —, Calculated Dependence

A sufficient condition for realization of vapor-phase combustion of the particle of metal is that the combustion temperature (considering radiation losses) exceed the boiling point of the metal. In this case, the chemical reaction of oxidation obviously cannot occur heterogeneously on the surface of the melted particle (drop) of metal, but rather occurs at some distance from its surface in the vapor phase. We must emphasize that fulfillment of the condition of vapor-phase combustion depends not only on the properties of the metal itself, but also on particle diameter, composition of oxidizer, its pressure and temperature.

The process of combustion of particles of metals for which this condition is fulfilled (they are called low-boiling metals) has a great deal in common with the combustion of drops of liquid fuel. However, since during combustion of metals the combustion products formed are primarily condensed, in the construction of the theory of vapor-phase combustion of metal particles we must consider the radiation transfer of heat from the zone of the reaction to the surface of a particle and to the surrounding medium and the influence on the process of combustion of the evaporation of the oxides formed. This becomes particularly significant for the case of combustion of metal particles in pure oxygen. /115

The theory of the combustion of particles of low-boiling metals developed in [13-15] (considering these peculiarities) allows us to calculate the characteristics of the process, particularly the time of combustion of a particle. It has been shown that the ratio of combustion time of a nonmoving metal particle to the square of its initial diameter is not constant, as is the case for drops of liquid hydrocarbon fuel, but rather increases with increasing particle diameter. This result

agrees with the experimental data produced upon investigation of the combustion of magnesium particles [16]. Comparison of the calculated dependences of combustion time of a particle on the content of oxidizer in the medium, temperature and velocity of the stream for magnesium and aluminum [14, 15] indicates good qualitative and satisfactory quantitative agreement[1]. As an example, Figure 4 shows a comparison of the calculated dependence of relative time of combustion of aluminum particles on the volumetric fraction of oxygen in the medium with the experimental data of [17].

In recent times, significant progress has been achieved in our understanding of the process of flame propagation in a gas suspension of solid fuel particles [18-21]. In particular, the significance of conductive and radiation heat transfer in this process has been analyzed and it has been shown that with the radiation mechanism of heat transfer, the velocity of flame propagation may be very high, u = 1-10 m/sec.

As applicable to the propagation of a flame in a gas suspension of metal particles, the role of heat transfer by radiation apparently takes on the predominant significance, since in this case the reaction products are formed primarily in the condensed form and a high combustion temperature is achieved. These factors allow us to explain the high velocity of propagation of the flame in an air suspension of aluminum particles observed in the experiments of [22].

With the radiation mechanism of flame propagation, the thickness of the heated zone (flame thickness) is equal as to order of magnitude to the characteristic radiation path length $L_u \approx 1/nS$ (n is the number of particles suspended per unit volume, S is the area of their cross section of absorption) and is usually about 1 meter. For a flame with such a great thickness, comparable to the dimensions of the reaction vessel or combustion chamber, the unstable stage of propagation of the flame becomes significant. This problem is studied in [23, 24].

In conclusion, we note that although a number of problems related to the ignition and combustion of metal particles with the propagation of a flame in the aerosols of such particles have been studied in the works of Soviet and foreign scientists, in general the analysis of the problem is still far from completion.

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[1] In addition to magnesium and aluminum, the low-boiling metals under certain conditions also include lithium and beryllium.

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THE USE OF METAL FUEL IN NUCLEAR ON-BOARD POWER PLANTS FOR SPACE

L. A. Kvasnikov

The promise of the use of metal fuels for spacecraft was first noted in 1909 by the remarkable Soviet scientist, talented engineer and inventor, enthusiast of interplanetary voyages, F. A. Tsander [1].

While turning great attention to the problem of the engine, space vehicle, and flight dynamics, he also understood the unavoidable necessity of on-board power for the spacecraft. The same on-board power which, on the one hand, supports the operation of the apparatus and all systems of the spacecraft, its scientific instruments and, on the other hand, allows us to use the most effective electrical reaction engines, based on a metallic working component.

Future interplanetary spacecraft should, in the opinion of F. A. Tsander, also be astronomical laboratories using laboratory instruments for observation. However, in order to support the operation of these instruments, there must be sources of electric power on board the spacecraft. This power can be used /117
to provide for the daily needs of the crew, cleanse the air, support a greenhouse, as was noted by F. A. Tsander in his article "The Problem of Superaviation and Ordinary Problems" [1, pp. 436-441].

He suggested that on-board power plants be used also to reduce the danger of meteors. Here is what he has to say on this subject in his article "Deflection of Meteors," "If, for example, we collect solar energy with a large convex mirror connected to the spacecraft, evaporate water in a boiler using the heat collected and use the steam to drive a steam engine, and use it to drive a generator and the electric power of the generator to drive an instrument producting cathode rays, we can constantly eject into space a large quantity of negative electricity." The scientist believed that this charge would slow down meteors.

At the present time, power installations based on alkali metal vapors are well known, synthesizing both of the suggestions of F. A. Tsander: on-board power and the use of metal working components, which are more effective than water. These suggestions have been most completely embodied in the electric reaction engines which have been developed. It is here that on-board power plants based on liquid metal working fluids are used, and the power they develop, in addition to satisfying the on-board needs, is consumed to create an impulse by ejecting a

stream of charged ions of metallic components such as cesium or a mixture of charged particles of different signs into space. As a result, high specific parameters of the reaction engine are hopefully produced. At the same time, the use of the metal of structures of the rocket as the working components becomes more realistic.

The liquid metal heat transfer medium in the circuits of the power plant can, if necessary, be fed directly into the motor from the resources which are used up after each section of the installation is switched off.

In his work "The Use of Metallic Fuel in Rocket Engines," F. A. Tsander stated that lithium, which has the greatest specific energy capacity, was one of the most promising metals. In 1928-1929, he performed experiments on the combustion of alloys of magnesium, aluminum and other metals, noting that the use of metallic fuel should increase the exhaust velocity in the engine. The direct conversion of energy to electricity was at that time not sufficiently developed. The first fuel elements providing for the conversion of the energy of chemical fuels directly to electric power, developed by Grove (1839) and P. N. Yablochkov (1880's) were little known, so that F. A. Tsander did not have the opportunity to extend the idea of metal fuels to the direct production of electric power [2].

"Cold combustion" in a fuel element occurs if the cavities of the working components are separated by an ion exchange membrane or electrolyte with ionic conductivity of one of the components, while the metal electrodes adjacent to the membrane are connected by a conductor through the useful load. Due to the energy stored in the separated components, the ions of one of them will be captured from the electrolyte by the other. The flow of ions from the electrolyte and the corresponding quantity of electrons from the adjacent electrode will be replaced by ionization on the second electrode of the corresponding component, the ions of which pass through the electrolyte, while the electrons pass through the external electric circuit and useful load. Thus, the energy of the chemical components of the fuel will be expended in the external and internal resistance of the electric circuit, and when it is opened the potential difference, increasing to the value of the emf, /118 will characterize the energetic efficiency of the system of components in question.

As F. A. Tsander noted correctly, the use of metallic components should provide in this case the most favorable power-to-weight characteristics of the installation. It is interesting to compare the data which he presents for a number of metallic fuels reacting with oxygen and the emf developed upon "cold combustion" and the specific power capacities of the same

systems. The components suggested by F. A. Tsander allow us to develop not only higher exhaust velocities, but also higher emf and specific power capacities.

Metallic components are of maximum interest in combination with the use of nuclear power. The need to use nuclear on-board power installations in space is dictated by the increasing level of power consumption of space vehicles, since the effectiveness of performance of programs is determined by the power supply available.

The first power units embodied in operating models were the simplest and, apparently, most reliable systems available, with the electron energy conversion cycle.

The "Romashka" nuclear power plant made in the USSR and the "SNAP-10A" power plant, made abroad, the first nuclear power plant launched into space, were low power systems and therefore were not distinguished by their high power-to-weight characteristics. The thermoelectric power converter which they use was of low efficiency and therefore, probably, could not provide sufficiently good power-to-weight characteristics for high power installations [3].

The power-to-weight characteristics of on-board installations are related to the specifics of the application of a nuclear reactor of typical asymptotic type. In the area of low powers, the specific mass, i.e., the ratio of the mass of the installation to its electric power, approaches infinity due to the limitation of the minimum mass by the necessary secondary equipment, the conditions of criticality of the reactor, and depends little on the type of converter used.

In the area of higher power levels, the weight characteristics are determined by the conditions of heat exchange, as well as the efficiency characteristic for each power converter type. The specific mass of a power plant in this area depends decreasingly on the power level, asymptotically approaching a constant value.

Tests of a nuclear thermal emission power plant with a power production of several kilowatts undertaken in the USSR, as well as the results of testing of individual converters and planned developments of nuclear power plants of various power levels performed in a number of countries and presented at international conferences on thermal emission power conversion, show the promise of this type of installation with the electron conversion cycle for the achievement of higher efficiencies.

However, the combination of a nuclear reactor with a converter leads to the need to solve a number of problems related to the launching, matching of the capabilities for changing

load with the inertia of thermal processes, etc.

Installations with gas or vapor cycles, first suggested by F. A. Tsander for the requirements of space engineering, have their advantages in this case. The convenient operational characteristics and experience already accumulated in aviation and surface power engineering make it possible to use power plants with the Brighton cycle for the range of comparatively low powers, when the dimensions of the radiator are not limited by those of the spacecraft. The desire to reduce the expenditure of power in the compressor to increase the useful power of the installation leads to the use of low radiator temperatures and comparatively poor power-to-weight characteristics of the power plant as a whole, though the efficiency is quite high [4]. /119

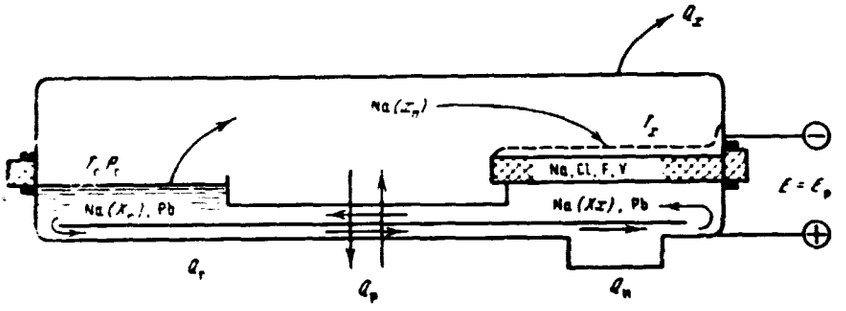


Figure 1. Diagram of a Fuel Element with Thermal Regeneration of the Components

The vapor cycle allows the temperature of the radiator to be increased and its dimensions to be decreased. It is important that it can be used in addition to steam turbine and magnetic-gas-dynamic power plants, as well as in plans with regenerative fuel elements. The regeneration of the working components can be achieved, for example, by evaporation of a low-boiling anode component from a cathode metal layer.

A process of this type has been used in the practice of electrometallurgy for the production of alkaline metals by electrolysis of melted salt electrolytes with a liquid lead cathode since 1949 [5], and also used for laboratory models of regenerative fuel elements [6].

Regenerative fuel elements with thermal regeneration of the working components are of interest for use in on-board nuclear power plants, since they combine the high effectiveness of the thermodynamic cycle of evaporation of one component from a metallic alloy, the product of a reaction, with the equally high energetic efficiency of electrochemical energy conversion.

Since plans with regenerative fuel elements do not require immediate utilization of the stored regenerated components, a change in the external load does not place such strict requirements on the system used to regulate the heat engineering portion of the installation, particularly the nuclear reactor.

One of the plans for a concentrated fuel element with thermal regeneration of the components is presented in Figure 1. In the particular case of this system, when the low temperature of the regeneration cycle provides rather high conductivity of the electrolyte, the pressure in the fuel element can be reduced to the level of the pressure in the regenerator and the anode component evacuated from the condenser directly by the fuel element, not requiring a special pump.

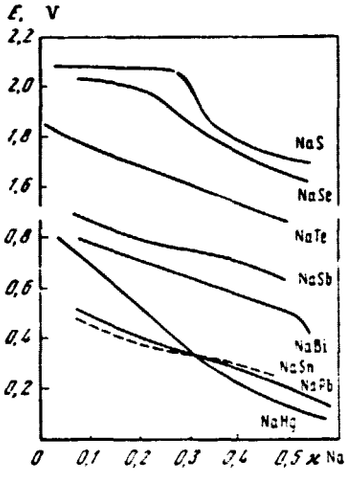


Figure 2. Electromotive Force of Element as a Function of Cathode Alloy Composition

The dependence of the electromotive force of the elements on the concentration of the anodic component in the cathodic alloy allows rather flexible variation of the parameters of the system. By selecting the proper composition of the cathodic component, as follows, for example, from Figure 2, for each given temperature of the element we can estimate the emf. /120

However, the electromotive force in turn is determined by the available specific work of the regeneration cycle, shown in Figure 3. For universality of our presentation, the cycle is constructed on an entropy diagram for a pure anodic component, for example sodium. Here, the process of thermal separation consists of the expenditures of energy for evaporation and for breaking of chemical bonds and is represented somewhat arbitrarily, while the processes of cooling and condensation of the vapor phase are rather correctly determined by the lower temperature of the cycle using the diagram.

If we know the maximum temperature of the cycle permissible on the basis of the conditions of long-term stability of the materials in the medium of the working components and optimize the lower temperature on the basis of the power-to-weight characteristics of the on-board nuclear power plant, it is not difficult to estimate the available specific work of separation per mole of the anodic component, expressed in volts: /121

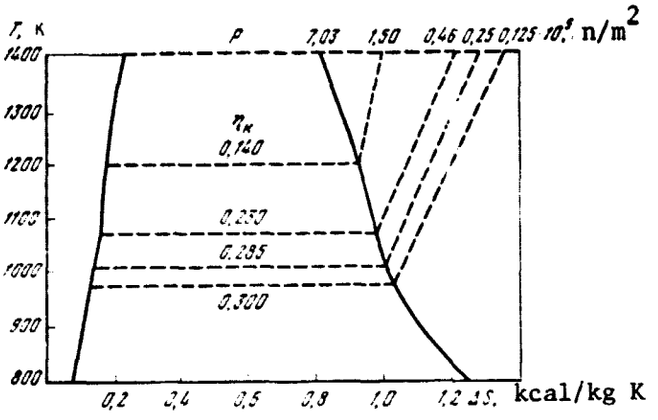


Figure 3. Regeneration Cycle of Anodic Component

$$E_p = 19{,}85 T_g \cdot 10^{-5} \lg \frac{P_{a.r}}{P_{a.x}}. \qquad (1)$$

If we can separate the temperatures of the cycle, for example by reducing the radiation temperature of the nuclear power plant, we can increase the specific work of separation. This leads, on the one hand, to a reduction in the concentration of the anodic component in the cathodic alloy and an increase in the electromotive force and, on the other hand, to an increase in the efficiency of the installation. The selection of the anodic component, in accordance with the dependences of saturated vapor pressure on temperature included in (1), will influence the specific work of separation and the emf of the fuel element.

Unfortunately, in separating the components by evaporating the low melting component in accordance to the curves of evaporation, an undesirable intermixing of a second component to the vapor phase occurs. This is most significant, for example, for a cathodic alloy based on lead. Therefore, we must take special measures, including periodic blowing out of the anodic cavities of the element in order to prevent their poisoning and a drop in the emf of the fuel element.

The specific work of separation in this case will exceed the emf, considering the necessary losses to evaporation of the second component:

$$E_p = 19{,}85 \cdot 10^{-5} T_{r} z \log \frac{P_{a.r}}{P_{a.x}} \left(\frac{P_{a.r}}{P_{a.x}}\right)^{\frac{1-\eta}{\eta}}. \qquad (2)$$

Determining the maximum possible value of emf for the given cycle temperatures and components, considering all losses, it is not difficult, using equation (1) to select a cathodic alloy and concentration if we have sufficiently detailed dependences of emf on concentration and temperature (Figure 2).

In a power plant with a regenerative fuel element, the concentration and emf will be established automatically as a function of the temperature levels or thermal mode and the external load.

In detailed evaluations of a power plant, we must consider the change in concentration of the cathodic component both along the electrode, determined by its gradual saturation with the anodic component, and the transverse concentration polarization, caused by saturation of the layers of the cathodic alloy adjacent to the electrolyte [7], particularly in modes of elevated current density.

As we reduce the voltages and current densities per element, these processes influence the power-to-weight characteristics of the power plant as a whole. Optimization of the rate of pumping of the cathodic alloy in the cathodic cavities of the elements allows the concentration losses to be decreased with intelligent limitation of the power of the pumps.

The limitations known from electrometallurgy on the diffusion of alkaline metals in alloys and the limitations which follow from this as to current allow us to estimate the working current density which can be achieved.

A second factor significantly influencing the current density is the electrolyte. The selection of a fused salt electrolyte based on alkaline metal halides in a porous matrix /122
represents some danger as concerns the strength of the system and requires comparatively high electrolyte and element temperatures, resulting from the fusibility of the electrolyte. The use of an aluminate thickened alkaline component in paste electrolytes requires special measures to increase strength. The use of solid electrolytes in the form of β-alumina could solve both the problem of the electrolyte and that of sealing with current separation of the cathodic and anodic cavities.

The maximum specific power of batteries of fuel elements corresponds to the mode when the current density is 50% of the short-circuit current. However, in a number of cases there is reason to reduce the power-to-weight characteristics of batteries by decreasing the current density and increasing the efficiency of the elements, since in this case the increase in weight of the battery of fuel elements is compensated by a decrease in the mass of the heat engineering equipment, nuclear reactor, its shielding and radiator, leading to an overall

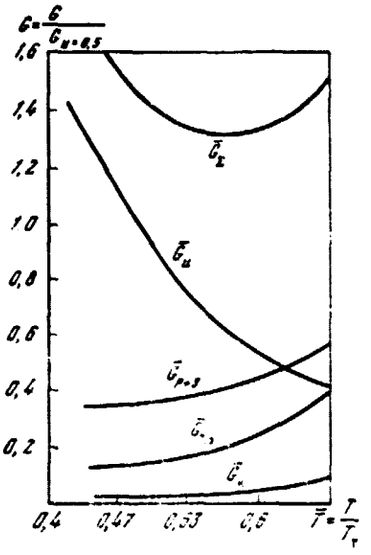


Figure 4. Influence of Cycle Temperature on Distribution of Masses in a Power Plant

improvement of the power-to-weight characteristics of the total on-board power plant.

A decrease in the lower temperature of the cycle causes a drop in the pressure of the vapor of the anodic component over the regenerated alloy and allows us to increase the specific work of separation, emf and efficiency of the installation.

However, as follows from the calculation, the results of which are presented in Figure 4, with the total reduction in mass of the reactor, heat engineering equipment and batteries of fuel elements, the specific mass of the radiator increases, leading to the need to select cycle temperature relationships on the order of T/T_r = 0.5-0.6. This relationship is indicated by the significant influence of permissible current density in the fuel element.

The masses of the component parts of the power plant are related as shown in Figure 4 to the mass of the radiator for T/T_r = 0.5.

The consumption of the anodic component, which determines the flow of heat through the radiator, is proportional to its atomic weight M_a, the current passing through the element I and the number of elements in the battery n:

$$G_a = 1.0363 \cdot 10^{-5} M_a I_n \text{ [g/sec]}. \qquad (3)$$

The reserve of the anodic component in the battery of fuel elements therefore can provide for power consumption on the order to 10% of the nominal power for 1 hour even with a height of the anodic cavity only on the order of 1 mm. The accumulation of the energy supplied will be primarily determined by the permissible change in concentration of the cathodic layer $\Delta\kappa$. The necessary flow rate of the cathodic layer at the initial concentration κ_0 in the stable mode will be

$$G_к = \left(\frac{1-\kappa_0}{\Delta\kappa} - 1\right)\left[\kappa_0 + (1-\kappa_0)\frac{M_к}{M_a}\right] G_a. \qquad (4)$$

This expression shows, in comparison to the anodic component, the need for a 6 to 7 times accumulating volume. As the concentration κ increases, the emf of the element will drop in accordance with Figure 2, which can be compensated to some extent by a decrease in the load and a change in the mode with respect to the volt-ampere characteristic of the element. /123

The power capacity of the working component stored in the battery of fuel elements can be used in the launch modes of the on-board power plant to heat the loops of coolant and working fluid, supply the pumps, etc. Its value can be estimated from the table of F. A. Tsander, supplemented by the specific power capacity and emf developed by the various components with oxygen.

Lithium	Aluminum	Beryl-lium	Magnes-ium	Hydrogen	Gasoline	Dimen-sionality
4730	3700	5430	3600	3240	2350	kcal/kg
6330	5560	6570	5500	5170	4430	m/sec
2,83	4,44	4,62	3,42	1,00	1,00	volts
2,42	2,36	2,47	2,57	2,93	—	kwhr/kg

The size of the buffer containers of the components and the permissible change in concentration of cathodic component should be optimized considering the starting and nominal modes as concerns the power-to-weight characteristics of the power plant as a whole.

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III

ASTRODYNAMICS

THE USE OF TANGENTIAL TRAJECTORIES TO LOWER THE HIGHLY ELLIPTICAL ORBITS OF ARTIFICIAL SATELLITES OF THE PLANETS

P. Ye. El'yasberg and N. A. Eysmont

On 8 June 1924, F. A. Tsander submitted to the Committee for Inventions a patent application for a spacecraft, the descent of which to the Earth was to be achieved by means of aerodynamic braking forces. The application stated in part, "...it is possible to enter the atmosphere of the Earth, descending by gliding and assisting the descent with a small engine.... In order to descend to the Earth or to another planet with an atmosphere, the flight must be directed so that it has a horizontal direction in the terrestrial atmosphere. At speeds of greater than about 8 km/sec, gliding flight at constant altitude should be performed so that the aeroplane flies in a spin and the air pressure on the wings is directed downward toward the Earth, not away from the Earth; at decreasing velocities, less than about 8 km/sec, it is possible to fly in the usual position" [1]. The Preliminary Analysis Bureau of the Committee considered Tsander's suggestion to be fantastic and refused to give him a patent for his interplanetary spacecraft. Over 40 years went by, and spacecraft, using, as Tsander suggested, aerodynamic forces as they return to Earth or landed on planets with an atmosphere became a reality. However, the problem of utilizing the atmosphere of a planet to transfer the spacecraft from a fly-by hyperbolic trajectory to an orbit around the planet as a satellite still cannot be solved by space technology today [2]. The main reason for this is the excessive requirements for accuracy of knowledge of the trajectory of the vehicle and the physical characteristics of the planet. When only the thrust of the engine is used to transfer the spacecraft to a low satellite orbit, the requirements for accuracy of knowledge of the trajectory of the vehicle and the physical conditions of the planet are significantly simplified, but the required energy expenditures simultaneously increase. Therefore, there is interest in a compromise version in which the vehicle would begin to shift from its hyperbolic orbit to a high elliptical orbit by means of the engine, then the necessary lowering of the orbit would be achieved by successive passages through the atmosphere at the pericenter of the orbit, the engine being used in this stage of flight only to control the braking process.

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We present below one possible method of controlling the movement of a vehicle in order to transfer it to a low orbit by braking in the atmosphere when incomplete information is available on the atmosphere of the planet and when there are errors in our knowledge of the orbital elements.

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Statement of the Problem

It is assumed that the vehicle is initially in an orbit with great eccentricity. The requirements for altitude of the pericenter of the orbit are given below. The field of gravity is considered central, the planet and its atmosphere -- spherically nonrotating. The aerodynamic quality of the satellite as it flies through the atmosphere is assumed equal to 0. The ballistic coefficient is taken as a constant. Under these conditions, we can state the problem of analysis of the characteristics of motion and control using measurement of the acceleration during movement through the atmosphere, i.e., we assume that the spacecraft carries an accelerometer as a sensing element in its control system. The actuation element is the engine, switched on outside the atmospheric sector. It is assumed that the control system can perform all necessary calculations in the time made available by the control process and in addition to the data from the accelerometer, can use the information on the orbital elements and characteristics of the atmosphere of the planet available, though this information does contain some error. The purpose of control is to provide the minimum time of transition of the satellite to a circular orbit with limitations as to permissible thermal modes of motion in the atmosphere.

Method of Control

The permissible thermal modes will be determined by the maximum equilibrium temperature on the surface of the satellite, which is cooled only by radiation.

We will limit ourselves to analysis of flight modes in which the oncoming gas stream can be considered freely molecular. The heat flux to an element of the surface of the body in this case is expressed by the formula [3] $Q = \alpha\rho v^3 \sin\theta$, where α is the accommodation factor, its value lying between 0 and 1; ρ is the density of the atmosphere; v is the velocity of the body; θ is the angle between the velocity vector of the incident stream and the surface element; in the following, we will assume $\theta = \pi/2$.

The acceleration n measured by the accelerometer at velocity v can be used to determine the heat flux, since Q is easily written as

$$Q = \alpha nv\frac{2mg}{SC_x},$$

where S is the cross-sectional area of the satellite; C_x is the aerodynamic drag factor; m is the mass of the satellite; g = 9.81 m/sec^2. If the radiant heat fluxes from the sun and planets are assumed constant throughout the orbit of the satellite, the maximum total heat flux and, consequently, the maximum equilibrium temperature will be reached simultaneously with the maximum of quantity (nv). For ballistic trajectories, in each rotation it is sufficiently accurate to consider max (nv) = $n_\pi v_\pi$, where the subscript π represents the parameters at the pericenter.

From this we can see that braking occurs in the minimum time if the value of $n_\pi v_\pi$ in each revolution is equal to the maximum permissible $(n_\pi v_\pi)_3$. The task of control is to select in the nonatmospheric section of each revolution the moment for switching on the engine, the time of the burn and the orientation of the thrust vector such that during the next pass through the atmosphere the following equation will be satisfied:

$$n_\pi v_\pi - (n_\pi v_\pi)_3 = 0. \tag{1}$$

Based only on the requirements for minimum fuel consumption for control, we would switch on the engine at the apocenter of the orbit. This conclusion is based on the fact that the derivative of pericenter altitude with respect to velocity reaches its maximum at the apocenter of the orbit, while the acceleration /126

$$n_x = \frac{\rho v^2}{2}\frac{SC_x}{mg} \tag{2}$$

is determined primarily by the altitude of the pericenter h_p, since the dependence of density ρ on altitude h is near exponential and for small values of $(h - h_0)$, the following approximation is sufficiently accurate:

$$\rho = \rho_0 e^{-\beta(h-h_0)}, \tag{3}$$

where ρ_0 is the density at altitude h_0; β is the reciprocal to the local value of altitude in a homogeneous atmosphere (4):

$$\beta = -\frac{d \ln \rho}{dh}(h_0). \tag{4}$$

Control Algorithm

In analyzing the control algorithm, we will assume that the engine provides an instantaneous velocity increment Δv_α at the apocenter of the orbit colinearly to the velocity vector. Then, for fixed r_α, v_α and function $\rho(h)$, the left portion of equation (1) is only a function of Δv_α, while the control algorithm is reduced to the solution of the nonlinear equation

$$n_2(\Delta v_\alpha) v_2(\Delta v_\alpha) - (n_\pi v_\pi)_3 = 0, \tag{5}$$

for calculation of the time of passage of the satellite through the apocenter and the direction of the velocity vector at the apocenter. These procedures are easily performed by known methods. However, since the values of v_α and r_α are the results of processing of several measurements not analyzed here, they, as was noted above, cannot be known precisely. The mean square deviation, for example, of the pericenter radius of the orbit of a satellite of Mars may reach several tens of kilometers. We must therefore have additional information, provided by the accelerometer, in the form of the acceleration as a function of time $n = n(t)$. Knowledge of the boundaries of maximum values of $\rho(h)$ in the form of the function $\rho_{max}(h)$ is necessary for selection of the radius of the pericenter of the initial highly elliptical orbit providing for satisfaction of the inequality $n_\pi v_\pi \leq (n_\pi v_\pi)_3$ for all possible deviations of orbital parameters from the nominal parameters.

The motion of the satellite in the atmosphere is described by the equation

$$\frac{d^2\mathbf{r}}{dt^2} = -\frac{\mu}{|r|^3}\mathbf{r} - \frac{n(t)\, g}{\left|\frac{d\mathbf{r}}{dt}\right|}\frac{d\mathbf{r}}{dt}, \tag{6}$$

where $\mathbf{r}$ represents the radius-vector of the satellite. Integration of this equation with the initial conditions at the boundary of the atmosphere, determined from the nominal elements of the orbit, and utilization of formula (2), allows us to find the

function $\rho = \rho(r)$. After using formula (4), we produce $\beta = \beta(r)$ for $r \geq r_\pi$, where r_π is the radius of the pericenter of the revolution in question. The quantity Δv_α necessary for assurance of the required mode of motion in the next revolution is easily determined by solving equation (5). Here, the need may arise to determine the value of the function $\rho = \rho(r)$ where $r < r_\pi$ for a revolution, during the atmospheric sector of which the acceleration was measured. The necessary expansion of the area of determination of function $\rho(r)$ is achieved by extrapolation using formula (3), replacing h with r and the subsript 0 with π: /127

$$\rho = \rho_\pi e^{-\beta(r-r_\pi)}, \qquad (7)$$

where $\beta = \beta(r_\pi)$; $r < r_\pi$.

The algorithm described above is applicable where $n(t) \geq n_{min}$, where n_{min} is the minimum threshold of sensitivity of the accelerometer.

Let us study the case when, with motion in the region of the pericenter, the acceleration is lower than n_{min} everywhere. Then in order to control the motion in the next section in accordance with equation (5) we can calculate the density using formula (7), considering that r_π is the radius of the pericenter of the preceding revolution; ρ_π is determined from a relationship (2), where we use $n_\pi = n_{min}$. The value of β in this case is taken as the maximum possible for the atmosphere of the planet where $r < r_\pi$ and the minimum possible where $r \geq r_\pi$. We can show that with this selection of ρ and β, control with values of orbital elements equal to the nominal will be provided by fulfilling the inequality $n_\pi v_\pi \leq (n_\pi v_\pi)_3$, meaning that the equilibrium temperature does not exceed its assigned value.

Methods and Results of Numerical Modeling of Flight

Figure 1c, as a function of the value of $(m/S_{c_x})nv$, shows graphs of the equilibrium temperature, defined on the assumption that the blackness factor $\varepsilon = 1$, the accommodation factor $\alpha = 1$. The graphs were constructed for radiant heat fluxes $Q_i = 2600$, 600 and 50 w/m^2, correspondingly equal to the heat fluxes from

the sun in the region of the orbits of Venus, Mars and Jupiter. The equilibrium temperature was determined from the well-known formula

$$T = \sqrt[4]{Q_\Sigma / \sigma}, \tag{8}$$

where Q_Σ is the total heat flux; σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \cdot 10^{-8}$ w/m^{2}deg^4).

We limited ourselves to analysis of modes of motion for which the equilibrium temperature is not over 350-390 C, which corresponds, as the figures show, to the maximum value $(m/S_{c_x})nv$ = = 250 kg/m^{2}m/sec. This means that for actual values of m/S_{c_x} = = (10-1000 kg/m^2) and possible values of v_π (from 3600 to 5000 m/sec for Mars to 43000-60000 m/sec for Jupiter), the permissible acceleration will amount to a fraction expressed in hundredths. The purpose of modeling was to estimate the nature of change of parameters of motion and total time of transition to an orbit with a high apocenter of 800 km for Mars and Venus and 7000 km for Jupiter, and also to estimate the effectiveness of the control algorithm with possible errors in the determination of orbital elements and measurement of acceleration. The parameters of true motion outside the atmosphere (where $n < 10^{-6}$) were determined from the formulas for conic sections, parameters of motion in the atmopshere were produced by integration of the equation

$$\frac{d^2\mathbf{r}}{dt^2} = -\frac{\mathbf{r}}{|r|^3}\mathbf{r} - \frac{\dots}{\dots}\frac{\partial \mathbf{r}}{\partial \dots}\frac{\partial \mathbf{r}}{\partial \dots}. \tag{9}$$

The atmosphere was assigned discrete values of density ρ_i for altitudes h_i. For altitudes $h_i < h < h_{i+1}$, the density was calculated by the formula /128

$$\rho = \left(\frac{\rho_i}{\rho_{i+1}}\right)^{-\frac{h-h_i}{h_{i+1}-h_i}}, \tag{10}$$

produced from (3) on the assumption that in the height interval (h_i, h_{i+1}) the density changes in accordance with (3).

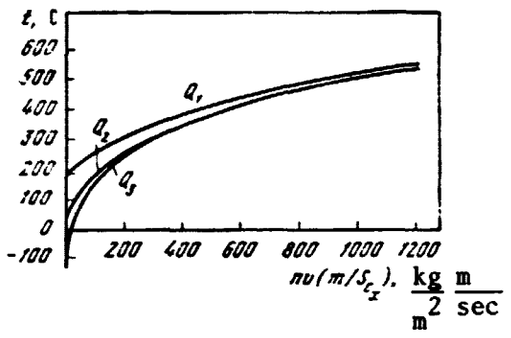


Figure 1. Equilibrium Temperature as a Function of Satellite Movement Parameters

Calculations were performed to estimate the influence of error in our knowledge of the radius of the pericenter on the operation of the control algorithm. In solving equation (5), we used parameters defined for trajectories, the radius of the pericenter of which differed by δr from r_π of the true orbit. Equation (5) was solved by the method of successive approximations. The formula below was applied repeatedly:

$$\Delta r_\pi = \frac{1}{\beta} \ln \frac{n_{\pi a}}{n_{\pi 3}}, \qquad (11)$$

where Δr_π is the required change in radius of the arbitrary pericenter; $n_{\pi a}$ is the value of acceleration at the pericenter for motion without control in a given revolution; $n_{\pi 3}$ is the required value of acceleration at the pericenter:

$$n_{\pi 3} = \frac{(n_\pi r_\pi)_1}{r_\pi}. \qquad (12)$$

Subsequently, using the formulas for conic sections, we defined the value of Δv_α necessary to produce the calculated value of Δr_π. During the course of the calculations, it was established that for eccentricity $e > 0.2$, we can use formula (12) without iterations, without introducing a significant methodological error. At the same flight stage, the value of $n_{\pi a}$ can be determined by linear extrapolation of acceleration n_π to the previous two revolutions. Calculations have shown that the errors in the value of the radius of the pericenter of a satellite of Venus located initially on a diurnal orbit, reaching values of ±100 km, lead to errors in acceleration $n_{\pi 3}$ of not over 2% $n_{\pi 3}$. Errors of ±50 and ±500 km in the value of the radius of the pericenter of Mars and Jupiter also lead to insignificant errors in $n_{\pi 3}$.

Figure 2 shows the change in eccentricity e, time of passage of the pericenter t_π, control impulse Δv_α, assigned

and realized accelerations $n_{\pi 3}$ and n_{π} for various number of revolutions in the flight of a satellite of Venus. Time t_{π} is counted from the moment of passage of the apocenter on the first revolution. The beginning of each revolution is taken at the apocenter. The ballistic coefficient $S_{c_x}/m = 0.1\ m^2/kg$, quantity $(n_{\pi}v_{\pi})_3 = 45$ m/sec (corresponding to an equilibrium temperature of 390 C), the period of the initial orbit is one day, the error in the value of radius of the pericenter $\delta r = 50$ km. One of the nonisothermal models of the atmosphere of Venus was used. As we can see from the figures, the entire process of development of an assigned acceleration occurs in the first 10 revolutions. The control impulse Δv_{α} is decreased from 2.8 m/sec to a practically 0 value, dropping the height of the pericenter from 266 to 158 km. During the next 150 revolutions, the pericenter drops by only 7 km, while the control impulses remain equal to 0 within the limits of accuracy of the construction of the graph, only gradually increasing to 0.14 m/sec on the last revolutions. The acceleration realized is practically indistinguishable from that assigned. The braking is completed in 351 revolutions and requires 102.5 days. /129

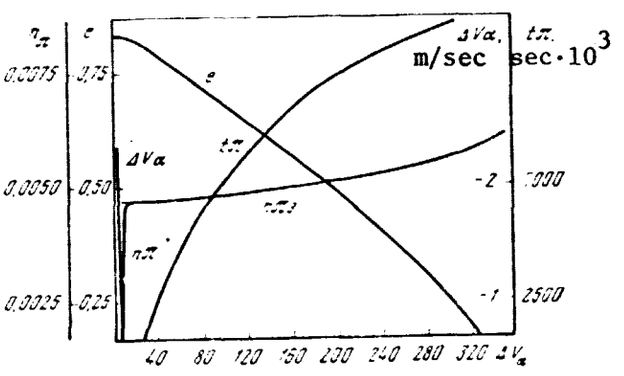


Figure 2. Change in Parameters of Motion of a Satellite of Venus with Increasing Number of Revolutions

The change in parameters of motion of a Mars satellite is of the same nature, but with the maximum equilibrium temperature of 370 C the braking from the initial half-day orbit is completed more rapidly -- in 10-15 days depending on the accepted model of the atmosphere.

Conclusions

Control of the motion of a satellite of a planet, achieving transition from a highly elliptical orbit to a low orbit by successive ballistic passages through the atmopshere in the region of the pericenter, can be achieved using a rather simple algorithm, utilizing information on the acceleration and elements of the osculating orbit. The requirements for accuracy of calculation and of burn to provide the change in velocity by switching on the engine in the region of the apocenter remain

comparatively loose. The time of braking with equilibrium temperatures maintained below 390 C and with a ballistic factor of 0.1 m^2/kg does not exceed 15 days for descent from a half-day orbit around Mars and 4 months from descent from a one-day orbit around Venus. For a satellite of Jupiter, the braking time is significantly greater (about 2 years). It can be decreased by using special design features to increase the ballistic factor and, correspondingly, the permissible values of acceleration. The expenditures of fuel for this maneuver are determined by the total control impulse required for velocity changes. This sum does not exceed 20 m/sec, which is more than an order of magnitude less than the sum of the Δv necessary to drop the orbit using only engine thrust, without atmospheric braking.

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ALGORITHM FOR CORRECTION OF THE PROGRAMMED MOTION OF A VEHICLE WITH A LOW-THRUST ENGINE

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In his works, F. A. Tsander attached great significance to /130 the investigation of prospective power plants. Thus, in the work "The Problem of Flight by Means of Reaction Apparatus," Tsander noted that "The rocket with its tremendous consumption of fuel and high thrust should be used only for the escape from the Earth's atmosphere and for acceleration to a speed of 8 km/sec," and "Subsequently, in interplanetary space with its tremendous distances and full possibility of using low thrust, it would be far better to use the pressure of light, which is given to us for free" [1]. The possibility noted by Tsander of effective utilization of "low thrust" has been realized in the utilization of low-thrust engines.

At the same time, Tsander developed other important problems of astronautics. Thus, in his articles on the theory of interplanetary voyages, he studied the problem of selecting trajectories for interplanetary flights to provide for the minimum consumption of fuel and problems of correction of interplanetary trajectory [2].

In the present work, we study the problem of compensation for errors in realization of the programmed motion of a vehicle by means of a low-thrust engine. Based on a priori information concerning the entire combination of perturbations, we analyze the problem of synthesis of a linear rule for a correcting control action providing the required accuracy of final position of the vehicle. As the optimality criterion, we have selected the dispersion of expenditure of fuel for realization of the programmed trajectory.

The specialty of a low-thrust engine is to impart to a flight vehicle extremely slight accelerations and, as a result of this, the long flight times of vehicles with the engine in operation place certain requirements on the control system. The control system of a flight vehicle with a low-thrust engine must be built so that adjustment of programmed control occurs during the process of powered flight.

We utilize a plan of successive corrections of the final position of the spacecraft. Based on the data provided by navigational measurements at a certain set of moments in time τ_i (moments of correction), corrections are introduced to the vehicle control program (correcting controls). It is assumed that observations are not complete, i.e., certain quantities are measured which do not truly and fully characterize the phase coordinates of the apparatus.

It is further assumed that the correcting control is undertaken by the main engine, the thrust and direction of thrust of which can be changed in discrete steps over certain constant values relative to the programmed values.

It is assumed that we know the probability characteristics of errors in the initial state of the apparatus, errors in measurement, and errors in realization of the programmed motion.

Assuming slight deviations of the parameters of motion of the spacecraft from the programmed values, the differential equations describing the perturbed motion of the spacecraft can be written as follows: /131

$$\begin{aligned} \dot{\mathbf{X}}(t) &= A(t)\mathbf{X}(t) + B(t)\mathbf{U} + \mathbf{S}, \\ \mathbf{X}(t_н) &= \mathbf{X}_н, \end{aligned} \tag{1}$$

where X(t) is the instantaneous vector of deviation of the phase coordinates of the spacecraft from the programmed values; U is the vector of control actions; S is the vector of perturbine actions; A(T), B(t) are the matrices of the corresponding dimensionalities, known functions of time.

The rule for the correcting control U_i acting over interval $[\tau_i, \tau_{i+1}]$, can be sought in the following linear form:

$$\mathbf{U}_i = \mathbf{k}(\tau_i)\mathbf{Y}_{meas}(\tau_i) = \mathbf{k}(\tau_i)G\mathbf{X}_{meas}(\tau_i) = k(\tau_i)[\mathbf{X}(\tau_i) + \Delta(\tau_i)], \tag{2}$$

where $Y_{meas}(\tau_i)$ is the vector of measured values of the observed quantities; $k(\tau_i)$ is the matrix of constant coefficients dependent on the moment of the ith correction; k = kG; Y = GX; $(\Delta\tau_i)$ is the vector of errors of determination of the coordinates of the spacecraft.

Assuming that in interval $[\tau_H, \tau_k]$ we introduce n correcting controls u_i (i = 1, 2,..., n) and considering $\Delta(\tau_i)$, X_H, S independent random vectors with mathematical expectations equal to 0, we can write a correlation matrix of finite deviations of the phase coordinates of the vehicle as follows:

$$\begin{aligned} V_x(t_н) = bV_x(t_н)\bar{b} + \sum_{p,\nu=n}^{p,\nu=1} \alpha_p V_{\Delta p,\nu}\bar{c}_\nu + \\ + \sum_{p,\nu=n}^{p,\nu=0} c_p \int_{\tau_p}^{\tau_{p+1}} \int_{\tau_\nu}^{\tau_{\nu+1}} \Phi(\tau_{p+1}, \xi_1) V_S(\xi_1, \xi_2) \Phi(\tau_{\nu+1}, \xi_2) d\xi_1 d\xi_2 \bar{c}_\nu \end{aligned} \tag{3}$$

where $\sim$ is the transposition symbol; $\tau_0 = \tau_H$, $\tau_{n+1} = \tau_k$; $V_{\Delta_{p,\nu}}$ is the correlation matrix of errors of measurement of coordinates of the vehicle at moments $t = \tau_p$ and $t = \tau_\nu$; $V_x(t_H)$ is the correlation matrix of the value of the vector of initial deviations of phase coordinates of the apparatus; $V_S(\xi_1, \xi_2)$ is the correlation matrix of perturbed accelerations acting on the vehicle at intervals $[\tau_p, \tau_{p+1}]$ and $]\tau_\nu, \tau_{\nu+1}]$, while the matrices α_ν, b, c_ν are calculated using the following recurrent relationships:

$$c_n = E, \quad d_\nu = \int_{\tau_\nu}^{\tau_{\nu+1}} \Phi(\tau_{\nu+1}, \xi) B(\xi) d\xi k(\tau_\nu),$$

$$c_{\nu-1} = c_\nu e_\nu \text{ where } \nu < n, \quad b = c_0 \Phi(\tau_1, t_H),$$

$$e_\nu = \Phi(\tau_{\nu+1}, \tau_\nu) + d_\nu, \qquad \alpha_\nu = c_\nu d_\nu, \tag{4}$$

where $\Phi(t, t_H)$ is the fundamental matrix for the system of homogeneous differential equations $\dot{X} = AX$, satisfying the condition $\Phi(t_H, t_H) = E$, where E is a unit diagonal matrix.

Determination of the rule of correcting control consists in seeking out matrices $k(\tau_i)$ and moments of correction τ_i providing the assigned accuracy of the final position of the vehicle and satisfying the minimum in the average consumption of fuel for correction.

The quantity of fuel mass expended in correction is looked upon as one of the components of the deviations vector X, i.e., the minimizing quantity is the corresponding diagonal element of /132
the matrix $V_x(t_k)$. The limitations placed on the dispersion of the final deviations of the coordinates of the vehicle will also be the corresponding diagonal elements of the matrix $V_x(t_k)$.

The solution of the problem of synthesis of the correcting control will be undertaken by an iterative method. In order to produce $V_x(t_k)$ in each iteration one must know the values of the fundamental matrix $\Phi(\tau_{i+1}, \tau_i)$, calculating the intergrals of the functions containing the fundamental matrix.

To do this, the entire interval $[t_H, t_k]$ is divided into m nodes, including t_H and t_k, and for these nodes the values of $\Phi(t_{i+1}, t_i)$ are calculated and memorized, as are certain

functions allowing one to produce the values of the integrals to be defined, included in (3) and (4).

The double integral

$$\int_{\tau_p}^{\tau_{p+1}} \int_{\tau_\nu}^{\tau_{\nu+1}} \Phi(\tau_{p+1}, \xi_1) V_S(\xi_1, \xi_2) \Phi(\tau_{\nu+1}, \xi_2) d\xi_1 d\xi_2$$

is a function of two variables and its memorization requires excessive digital computer memory volume. The problem is simplified if the double integral can be represented as the product of two single integrals.

If the components of the vector of perturbations S(t) have correlation functions such as

$$k(\xi_1, \xi_2) = \sigma^2 e^{-\alpha|\xi_2 - \xi_1|},$$

then this division can be achieved as follows:

$$e^{-\alpha|\xi_2 - \xi_1|} = \begin{cases} e^{\alpha\xi_1} e^{-\alpha\xi_2}, & \text{если} \quad \xi_2 \geqslant \xi_1; \\ e^{-\alpha\xi_1} e^{\alpha\xi_2}, & \text{если} \quad \xi_2 < \xi_1; \end{cases}$$
$$V_S(\xi_1, \xi_2) = V_1^{\pm}(\xi_1) V_2^{\pm}(\xi_2),$$

where V_1^+, V_1^-, V_2^+, V_2^- are matrices with the corresponding sign of the argument of the exponent. Here $V_2(\xi) = \tilde{V}_1(\xi)$.

Let us introduce the following functions to analysis:

$$J^+(\tau_{i+1}, \tau_i) = \int_{\tau_i}^{\tau_{i+1}} \Phi(\tau_{i+1}, \xi) V^+(\xi) d\xi,$$
$$J^-(\tau_{i+1}, \tau_i) = \int_{\tau_i}^{\tau_{i+1}} \Phi(\tau_{i+1}, \xi) V^-(\xi) d\xi,$$
$$I(\tau_{i+1}, \tau_i) = \int_{\tau_i}^{\tau_{i+1}} \Phi(\tau_{i+1}, \xi) V^+(\xi) J^-(\tau_{i+1}, \xi) d\xi.$$

The following cases are possible.

1. If $\tau_\nu \geq \tau_{p+1}$, i.e., $\xi_2 \geq \xi_1$, then

$$\int_{\tau_p}^{\tau_{p+1}} \int_{\tau_\nu}^{\tau_{\nu+1}} \Phi(\tau_{p+1}, \xi_1) V_S(\xi_1, \xi_2) \Phi(\tau_{\nu+1}, \xi_2) d\xi_1 d\xi_2 = J^-(\tau_{p+1}, \tau_p) J^+(\tau_{\nu+1}, \tau_\nu).$$

2. If $\tau_{\nu+1} < \tau_p$, i.e., $\xi_2 < \xi_1$, then

$$\int_{\tau_p}^{\tau_{p+1}} \int_{\tau_\nu}^{\tau_{\nu+1}} \Phi(\tau_{p+1}, \xi_1) V_S(\xi_1, \xi_2) \Phi(\tau_{\nu+1}, \xi_2) d\xi_1 d\xi_2 = J^+(\tau_{p+1}, \tau_p) J^-(\tau_{\nu+1}, \tau_\nu).$$

3. If $\tau_p = \tau_\nu, \tau_{p+1} = \tau_{\nu+1}$, then /133

$$\int_{\tau_p}^{\tau_{p+1}} \int_{\tau_\nu}^{\tau_{\nu+1}} \Phi(\tau_{p+1}, \xi_1) V_S(\xi_1, \xi_2) \Phi(\tau_{\nu+1}, \xi_2) d\xi_1 d\xi_2 = I(\tau_{p+1}, \tau_p) + \bar{I}(\tau_{p+1}, \tau_p).$$

Thus, we must calculate and memorize at each node the following matrix functions:

$$\Phi(t_{j+1}, t_j), \quad F(t_{j+1}, t_j) = \int_{t_j}^{t_{j+1}} \Phi(t_{j+1}, \xi) B(\xi) d\xi, \qquad J^+(t_{j+1}, t_j), \quad J^-(t_{j+1}, t_j), \quad I(t_{j+1}, t_j).$$

Having these matrix functions and performing the proper matrix operations with them, we can produce the correlation matrix $V_x(t)$ for an arbitrary control rule.

The recording of the correlation matrix $V_x(t_k)$ in form (3) allows us easily to find the analytic derivatives of the minimized and limited functions with respect to the parameters selected, which allows us to find the optimal control using the gradient methods of search for an extreme. In order to seek out the optimal correcting control, we used a modification of the differential gradient method, allowing us to construct our search from the initial point, without satisfying limitations such as inequalities and not allowing increments of matrices $k(\tau_i)$ which lead us away from the area of permissible accuracy of the final state of the apparatus. In the last case, the method operates as a projective method.

As an example of the application of the method suggested, we study the problem of acceleration of a spacecraft with a low-thrust engine in a zero-force field over a flight time equal to the time of departure of the apparatus from the field of gravity of the Earth for an initial acceleration of $0.2 \cdot 10^{-3}$ g_0. In studying the equations of perturbed motion of the space-

C. 2

craft, it was assumed that the perturbing factors acting on the vehicle in the process of the flight are:

1) Dispersion of initial conditions of position $\bar{r}_H$, velocity $\bar{u}_H$ and mass $\bar{m}_H$;

2) Errors in the measurement of the position of the vehicle Δr (only the position is measured);

3) Errors in realization of the program motion of the vehicle.

It was assumed that all of these random quantities and functions were distributed normally with zero mathematical expectation, correlation functions such as $k(t_1, t_2) = \sigma^2 e^{-\alpha|t_2-t_1|}$ and were not intercorrelated. Measurement errors were considered independent at different moments in time.

The desired correcting control was sought in the following linear form:

$$U_i = \xi_i k_i \bar{r}_{meas}(t_i), \tag{5}$$

where ξ_i are the selected gain factors; k_i are constants, which where $\xi_i = 1$ yield control $\bar{U}_i$, reducing deviation $\bar{r}(t_k)$ to 0 on the assumption that over the interval $[\tau_i, t_k]$ there are no perturbations, while at moments $t = \tau_i$ the deviations $\bar{u}(\tau_i) = \bar{m}_T(\tau_i) = 0$.

Thus, each of the elements of the correlation matrix $V_x(t_k)$ of finite deviations of coordinates of the vehicles is a function of 2n variables $\xi_1, \xi_2, \ldots, \xi_n, \tau_1, \tau_2, \ldots, \tau_n$ (n is the number of correcting controls). These quantities were selected from the condition of the minimum dispersion of additional fuel cost, necessary for assurance that the vehicle would reach the desired area of its final position.

Figure 1 shows the values of the gain factors ξ_i and moments of correction τ_i satisfying the minimum mean expenditures of fuel consumed for correction, and providing for fulfillment of the limitations placed on dispersion of the final deviations of position and velocity of the spacecraft. We can see that all moments of the beginning of the input of correcting control τ_i are located in the middle sector of the trajectory. The

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values of gain factor ξ_i decreasing with increasing number of the correcting control.

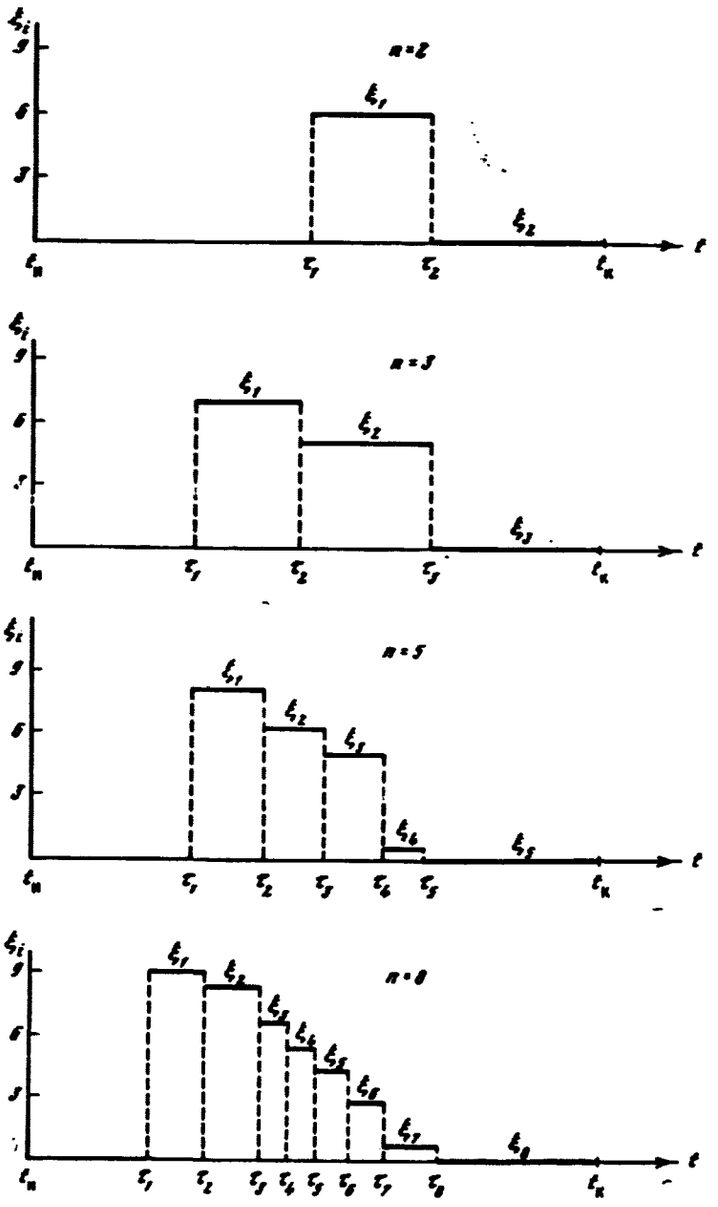


Figure 1

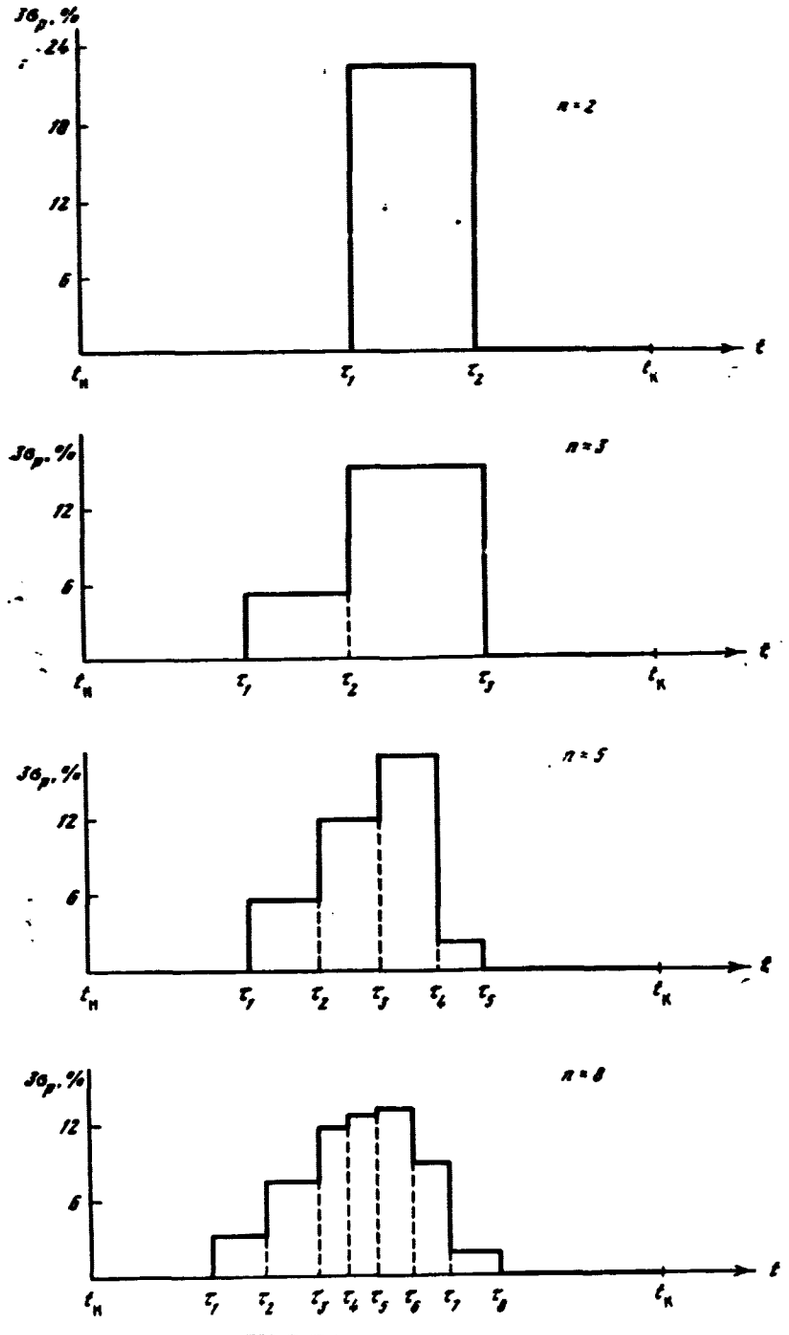


Figure 2

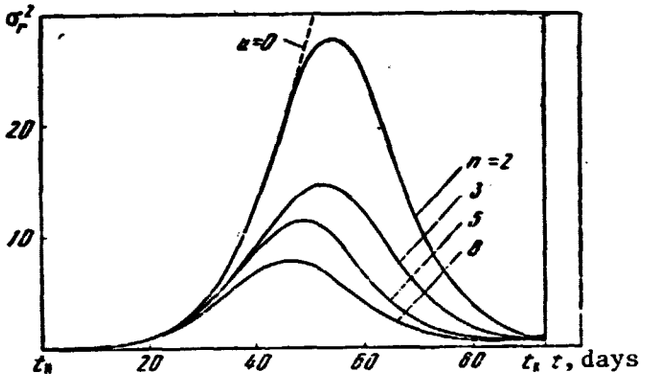


Figure 3

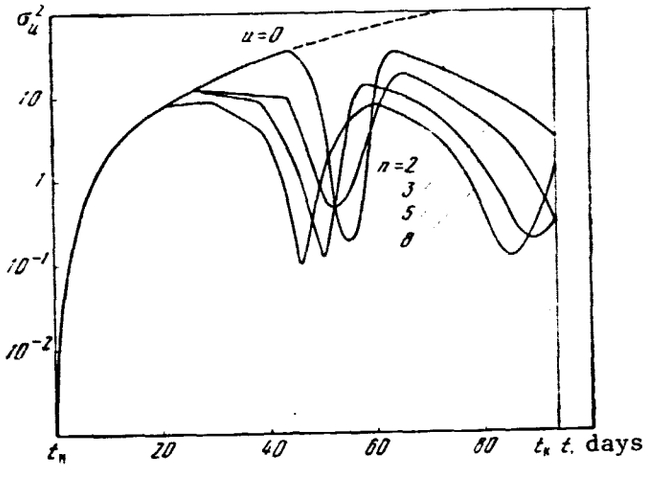


Figure 4

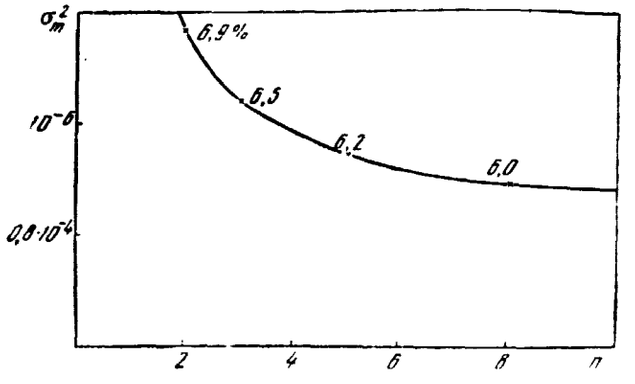


Figure 5

In the initial flight interval, deviations in the phase coordinates of the vehicle are slight, and therefore correction is not expedient here, since the correcting control would be performed using incomplete information and would include errors. At the end of the flight, correction is not expedient, since it requires great expenditures of fuel. If the values of the gain factor ξ_i are significantly greater than 1, the correcting control should be such that the error in the instantaneous position of the vehicle is eliminated in significantly less time than $t_k - \tau_i$. /137

Figure 2 shows the change in the maximum thrust of the correcting control (3σ) as a percentage of the programmed thrust during the time of the flight. We can see that the maximum thrust of the correcting control is located approximately in the middle section of control. As the number of correcting controls is increased, the maximum value of thrust decreases.

Figure 3 shows the change in dispersion of deviation $\overline{r}$ with flight time for various numbers

of correcting controls. We can see that as the number of correcting controls increases, the maximum dispersion of the position of the apparatus decreases.

Figure 4 illustrates the change in dispersion of deviations $\bar{u}$ with flight time for various numbers of correcting controls.

Figure 5 is dedicated to analysis of the change in dispersion of fuel consumption with an increase in the number of corrections. The mass of the entire vehicle is taken as the unit of measurement. On the right we show the figures corresponding to the maximum consumption of fuel for correction as a percentage of the consumption of fuel for the programmed trajectory. We can see that as the number of correcting controls increases, the value of the maximum expenditure of fuel decreases.

The preceding calculations indicate that the maximum thrust of the correcting control is 10-20% of the thrust of the programmed motion. This emphasizes once more the idea of F. A. Tsander of the effectiveness of utilization in interplanetary space of small forces which, in this case, are used to correct the program trajectory.

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THE ORIENTATION OF A SOLAR SAIL

V. I. Popov and I. O. Yanov

The idea of utilization of the force of the solar wind for interplanetary flights was first studied by F. A. Tsander [1, pp. 361-381]. He analyzed the problem of the necessary size, weight and strength of a solar sail (SS) and came to the conclusion that "In interplanetary space, with its tremendous distances and possibility of using extremely small thrust, it would be far better to use the free pressure of light or to transmit light energy over great distances using extremely thin mirrors" [1, p. 277].

When flying by means of an SS, it must be oriented in relationship to the sun at the proper angle for a long period of time. This is best done using a passive orientation system, utilizing solar pressure. The use of this type of system is explained by the following factors: a) long time of operation of /138
the system; b) high moment of inertia of the SS (three orders of magnitude greater than the moment of inertia of modern interplanetary spacecraft); c) low requirements for accuracy of orientation; d) comparatively high moments of forces of solar wind pressure (four orders of magnitude greater than the moment of gravity for a heliocentric orbit); e) the possibility of using the SS as a solar rudder.

In this work, we shall analyze several passive SS orientation systems. We will study the dynamics of the libration movement of one system for orientation of SS at any desired angle to the sun and the use of the SS as a solar rudder.

We will use the following symbols in our work: J -- main central moment of inertia of the entire system; ℓ -- length of bar; α, α_1, α_2, ϕ, η -- see Figures 2-4; θ -- angular bend of rod due to uneven thermal load of the sun's rays; β -- angular deviation of var due to nonrigidity of structure; a_c -- reflection factor of SS; m, m_c -- mass of body of spacecraft and SS respectively; R -- radius of SS; k_0 -- maximum curvature of bar due to thermal bending; τ -- time constant of thermal bending of bar; ω_y, δ_y -- frequency and coefficient of attenuation of natural elastic oscillations of structure; p_0 -- solar pressure; S -- area of SS; Sd -- area of additional blades; ϕ_c -- angle of visibility of sun; r -- radius of body of spacecraft; P -- surface tension in film of SS.

Some Systems for SS Orientation

F. A. Tsander, in his works, noted that "The screens should rotate about their central axes in order to give them rigidity" [1, p. 268]. Let us find the speed of rotation of SS, based on the condition that for any point on the SS the angular deviation of the tangential plane from the plane perpendicular to the axis of rotation must not exceed 6°. For $m = m_c = 10^3$ kg, $S = 10^5$ m^2, $p_0 = 0.45$ dyn/m^2 we have $\omega_r = 0.37$ degrees per second.

A passive method has been suggested for achievement of stability of the orientation of a rotating spacecraft with respect to the sun, with simultaneous stabilization of the rate of rotation [2, 3]. The method consists in installation on the rotating SS of corner reflectors or absorbing-reflecting blades (Figure 1), creating a torque due to the force of radiation which would force the axis of rotation of the SS to precess in the direction toward the sun. Stabilization of the rate of rotation requires the installation of additional blades controlled by means of a centrifugal regulator.

The area of the blades necessary for precessing the axis of rotation of an SS at 10 revolutions per year for a tracking error of 12° for $m = 10^3$ kg, $S = 10^5$ m^2, $\omega_r = 0.37$ degrees/sec, is $S_d = 2 \cdot 10^3$ m^2. This high value of S_d is the primary shortcoming of passive systems of orientation of rotating SS. Another shortcoming of these systems is the orientation of the plane of the SS only at an angle of 90° to the rays of the sun. In many cases, this is not sufficient. For example, for a transition from a circular orbit around the Earth to a parabolic orbit, the orientation of the SS must be changed twice in each revolution [1, p. 367].

Let us study nonrotating SS. F. A. Tsander called for unloading of the outer edge of the SS "by a built-in wire or thickened portion" [1, p. 375]. This can be used to give a nonrotating SS the necessary rigidity. The "thickened area" could be, for example, an inflated hose coated with vinyl monomer which would polymerize under space conditions, forming a rigid structure [4]. /139

1. The orientation system (Figure 2) consists of four additional blades attached to the edge of the SS. As angles α_1 and α_2 change, the angle of orientation of the SS ϕ also changes. Considering the blades to be fully reflective, we can write this dependence analytically

$$\sin^2(\varphi + \alpha_1)\cos\alpha_1 = \sin^2(\varphi - \alpha_2)\cos\alpha_2. \qquad (1)$$

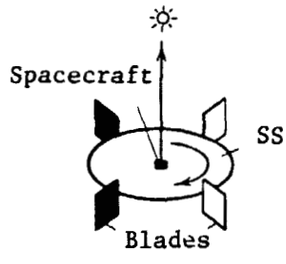


Figure 1

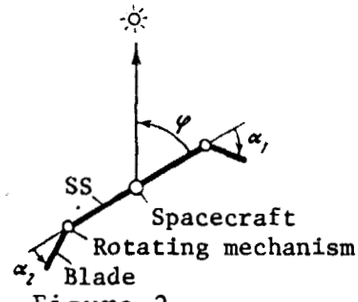


Figure 2

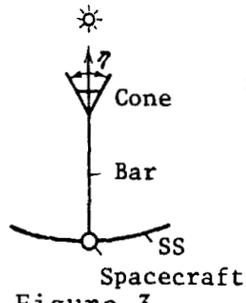


Figure 3

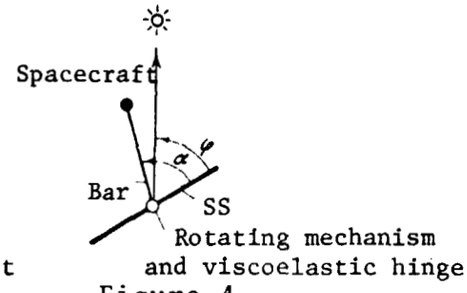


Figure 4

Each position of equilibrium determined by condition (1) has its own natural frequency of slight oscillations of the system about this position:

$$\omega = \left\{\frac{2RS_d p_0}{J}\left[\cos\alpha_2 \sin 2(\varphi-\alpha_2) - \cos\alpha_1 \sin 2(\varphi+\alpha_1)\right]\right\}^{1/2}. \qquad (2)$$

For each ϕ, we can solve the problem of the conditional extreme of function (2) under conditions (1). The solution to this problem is presented in Figure 5. We can see from the figures that in the optimal case of changing angles α_1 and α_2, we can change the angle of orientation of the SS almost linearly within limits of 0 to 90°; the natural frequency of the slight oscillations is changed in this case only by a factor of 1.6.

In order to increase the natural frequency of the slight oscillations and introduce damping, the additional blades are attached by means of bimetallic plates [5].

2. The system of orientation (Figure 3), suggested in [6], consists of a parabolic SS and bar with a cone which is

located at the focal point of the parabolic SS. The position when the axis of symmetry of the SS is directed toward the sun is stable. With ideal focusing, the natural frequency of slight oscillations of the system about the position of equilibrium /140

$$\omega \sqrt{\frac{p_0 S l a_c \sin \gamma_i}{J_{\varphi_c}}} \tag{3}$$

is two orders of magnitude higher than the natural frequency (2) of the preceding system (see Figure 2).

The parabolic shape of the SS can be generated by the light pressure itself. To do this, the body of the spacecraft is attached by means of straps to a circular hose, which creates surface tension in the film of SS. The SS then takes on the parabolic shape:

$$u=\frac{(1+a_c)\, p_0 m}{4P\,(m+m_p)}\,(R^2-x^2). \tag{4}$$

where u is the deviation of an element of the SS from the plane of the circular hose; x is the distance from the center of the SS to the element of the SS in question.

However, this system (see Figure 3) has a number of shortcomings:

a) The dependence of the focal length of the parabola

$$F=P\,(m+m_c)/p_0 m\,(1+a_c) \tag{4a}$$

on the tension of the film of the SS and solar pressure, which in turn depends on the distance to the sun. This leads to the fact that with slight deviation of parameters P and p_0, natural frequency (3) decreases by several times;

b) The high energy density striking the cone;

c) The orientation of the plane of the SS only at an angle of 90° to the sun's rays.

3. Another orientation system (Figure 4) is simpler. In order to create a reproducible moment, this system utilizes nonideal reflection of the sun's rays from the surface of the SS and displacement of the center of mass of the system from the

plane of the SS by means of the bar (see Figure 4).

By changing angle α, we can change the angle of orientation of the SS

$$\varphi = \operatorname{arctan}\left(\frac{1 + a_c}{1 - a_c}\cot\alpha\right). \tag{5}$$

The natural frequency of slight oscillations of the system

$$\omega = \sqrt{\frac{3lmp_0(1 - a_c)\sin\alpha}{J(m + m_c)}}. \tag{6}$$

The graphs of functions (5) and (6) are shown in Figure 6. We can see from the figure that in order to change the angle of orientation of the SS between 10 and 90°, we must change angle α between 54 and 90°; the natural frequency in this case changes by only 1.1 times.

In order to introduce damping to the system, we can utilize nonrigidity of the structure or uneven heating of the bar by the sun's rays [7]. Let us study this problem in more detail on the example of one system (see Figure 4).

Dynamics of One SS Orientation System

In order to produce the equations for the planar angular motion of the system (see Figure 4), we make the following assumptions:

1) We consider the angular deviations of the bar due to nonrigidity of the structure (β) and thermal bending (θ) to be slight quantities;

2) We ignore the mass of the bar and the moment of inertia of the body of the spacecraft;

3) We ignore oscillations of the SS, since the natural frequencies of these oscillations $\omega_k = \mu_k\sqrt{\pi P/m_c}$ (where μ_k is the root of the Bessel function of the first kind of zero order) or at least two orders of magnitude greater than the natural frequency of the slight oscillations of the system (6). /141

Considering these assumptions, we can write the equations of motion

$$
\begin{aligned}
&i\ddot{\varphi} = 2\delta_y\dot{\beta} + \omega_y^2\varphi,\\
&i\ddot{\varphi} + \ddot{\beta} - \tfrac{1}{2}\ddot{\theta} = \frac{Sp_0}{m_c l}\sin\varphi\Big[(1-a_c)\sin\Big(\alpha+\frac{\theta}{2}-\beta-\varphi\Big) -\\
&\quad - 2a_c\sin\varphi\cos\Big(\alpha+\frac{\theta}{2}-\beta\Big)\Big],\\
&\dot{\theta} + \theta = k_0 l\Big\{\Big[\sin(\alpha-\varphi) - \frac{r}{l}\cos(\alpha-\varphi)\Big]f\Big[\frac{l}{r}(\alpha-\varphi)\Big] +\\
&\quad + a_c\Big[\sin(\alpha+\varphi) - \frac{R}{l}\sin\varphi\Big]f\Big[\frac{R\sin\varphi}{l\sin(\alpha-\varphi)}\Big] + a_c\frac{R}{l}\sin\varphi\Big\},
\end{aligned}
\tag{7}
$$

where

$$
i = \frac{J(m+m_c)}{mm_c l^2},\quad f[x] = \begin{cases} 0 & |x|<1,\\ 1 & |x|\geqslant 1.\end{cases}
$$

Function f is introduced to consider the shading of the bar by the body of the spacecraft and the illumination of the bar by the rays of the sun reflected from the SS.

Suppose the system moves near the position of equilibrium, in which case equation (7) can be linearized:

$$
\begin{aligned}
&i\ddot{\varphi} = 2\delta_y\dot{\beta} + \omega_y^2\varphi,\\
&i\ddot{\varphi} + \ddot{\beta} - \tfrac{1}{2}\ddot{\theta} = -\omega^2 i(\varphi-\varphi_0) - B\beta + \tfrac{1}{2}B(\theta-\theta_0),\\
&\dot{\theta} + \theta - \theta_0 = -2ci(\varphi-\varphi_0),
\end{aligned}
\tag{8}
$$

where ω is as in formula (6), $B = p_0 S\sin^2\varphi_0(1+a_c)/m_c l\sin\alpha$, $2ci = k_0 l\times$ $\times\Big\{\Big[\cos(\alpha-\varphi_0) + \frac{r}{l}\sin(\alpha-\varphi_0)\Big]f\Big[\frac{l}{r}(\alpha-\varphi_0)\Big] - a_c\frac{R}{l}\sin\varphi_0 - a_c\Big[\cos(\alpha+\varphi_0) - \frac{R}{l}\sin\varphi_0\Big]f\Big[\frac{R\sin\varphi_0}{l\sin(\alpha+\varphi_0)}\Big]\Big\}$, φ_0, θ_0 is the solution to equation system (7) where $\dot{\phi} = \dot{\theta} = \dot{\beta} = 0$.

Let us write the sufficient conditions for stability of the /142 system (8):

$$
\begin{aligned}
&\tau > 0,\quad \delta_y > 0,\quad \omega^2 > 0,\quad \omega_y^2 > 0,\\
&0 < -c < \omega^2/B < 1.
\end{aligned}
\tag{9}
$$

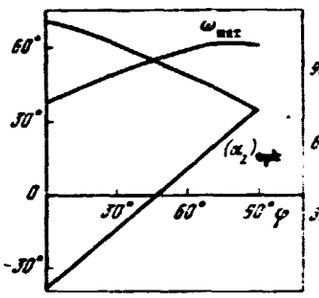


Figure 5

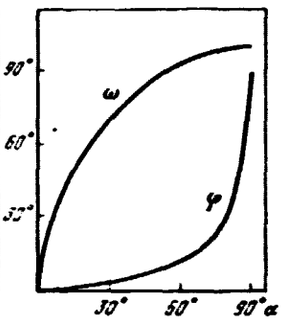


Figure 6

It follows from the condition of stability (9) that the thermal bending of the bar should be negative, i.e., the shaded side of the bar should receive more thermal energy than the illuminated side. The bar may have apertures located along spiral lines for this purpose [8].

Let us transform formula (6)

$$\omega^2 = \frac{2(1-a_c)p_0 S}{m_c R}\frac{\sqrt{i-1}}{i}\sqrt{\frac{m}{m-m_c}}\sin\alpha.$$

We can see from this expression that the natural frequency of slight oscillations of the system is maximal where i = 2. For i = 2, a_c = 0.8, we can use condition (9) to find the range of change of angle of orientation of the SS, in which the system is stable: $12° \leq \phi_0 \leq 90°$.

Let us study the problem of minimization of the time of damping of amplitude of natural oscillations by a factor of 20 for two particular cases:

1) Zero elastic deformations, i.e., $\beta \equiv 0$:

$$t_{min} \approx \frac{10}{\omega},\quad c_{opt} \approx -\frac{0{,}85}{B\omega^2 - 0{,}15},$$
$$\tau_{opt} \approx \frac{0{,}7(B\omega^2-1)}{\omega(B\omega^2-0{,}15)};$$

2) Zero thermal bending of the bar, i.e., $\theta \equiv 0$:

$$t_{min} \approx \frac{7.5}{\omega}, \qquad (\delta_y)_{opt} \approx 1.4\omega,$$

$$(\omega_y)_{opt} \approx \omega, \qquad B_{opt} \approx 3\omega^2.$$

Thus, the use of a viscoelastic hinge to damp the natural oscillations of the SS by 1.3 times is more effective than the use of thermal bending of the bar, although the latter method is simpler in the design respect and more reliable under space conditions.

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ENTRY CORRIDORS INTO THE ATMOSPHERE OF A PLANET FOR THE MANEUVER OF TRANSITION FROM A HYPERBOLIC TRAJECTORY TO A SATELLITE ORBIT AROUND THE PLANET

N. A. Eysmont

A broad range of problems concerning the study of the planets is most effectively solved using artificial satellites. Among these problems are cartography of the surface, determination of the parameters of the atmosphere and the shape of the planet, study of its magnetic field, radiation belts, magnetosphere, etc. /143

This leads to the need to perform research and development to find the most economical and reliable methods of delivering scientific instrument packages to orbits around the planets.

If the planet has an atmosphere, during the stage of transition from a hyperbolic trajectory to an orbit around the planet, the necessary fuel consumption can be reduced by using the aerodynamic drag of the spacecraft. The idea of using the aerodynamic drag of a spacecraft to scrub off speed was first suggested by F. A. Tsander [1] as a method of saving fuel as spacecraft returned to the Earth. In my own development of the idea of Tsander, I shall study the maneuver of aerodynamic braking, intending to shift the spacecraft from a hyperbolic trajectory to an orbit around a planet. The maneuver consists in that after the vehicle enters the atmosphere and is decelerated to the required speed, it leaves the atmosphere and then, by proper utilization of its rocket engines, is put into the required orbit.

I note that, no matter what the assigned orbit of the satellite, after departure from the atmosphere at least one velocity change will be necessary to shift the spacecraft into this orbit. (The problem is studied in its impulse statement.) Otherwise, the vehicle would once more enter the atmosphere. If repeated dipping into the atmosphere is allowed, a velocity increment is always necessary after the last dip into the atmosphere and may be required on previous departures of the spacecraft from the atmosphere. We will discuss the case when the vehicle passes through the atmosphere but once.

Let us establish the conditions which must be satisfied by the parameters of the trajectory upon departure from the atmosphere in order that the sum of the velocity increments for transfer to an orbit around the planet, achieving the assigned altitudes of pericenter and apocenter, might be minimal.

Suppose the trajectory of transfer is optimal in the sense mentioned above and satisfies also the requirement $r \leq r_{max}$, where r is the distance of the vehicle from the center of the planet, r_{max} is the maximum permissible distance based on the transfer trajectory. We can then imagine the following cases, depending on the value of the osculating elements of the trajectory upon departure from the atmosphere: 1) $r_{\alpha H} > r_{max}$; 2) $r_{\alpha k} \leq r_{\alpha H} \leq r_{max}$; 3) $r_{min} \leq r_{\alpha H} < r_{\alpha k}$. Here, the subscript α is attached to the apocentric distance, the subscript H corresponds to the parameters of the orbit at the moment of departure from the atmosphere, the subscript k to the parameters of the assigned orbit of the satellite.

Let us limit ourselves to analysis of versions 2 and 3. These cases of transition from orbit H to k belong, according to the classification of [2], to the class of type II-I transitions. As was shown in [3], where $r_{\alpha k} > r_{\alpha H}$, the optimal transitions in this class may be either two-burn transitions with a burn at the initial point of the orbit H (at the boundary of the atmosphere in our case) and at the apocenter of orbit k, or three-burn transitions with burns at the initial point of orbit H, at the apocenter of the transition orbit with $r_\alpha = r_{max}$ and at the pericenter of orbit k. Where $r_{\alpha k} < r_{\alpha H}$, the optimal transition may be a two-burn transition with burns at the apocenter of orbit H and the pericenter of orbit k or a three-burn transition of the same type as where $r_{\alpha k} > r_{\alpha H}$. /144

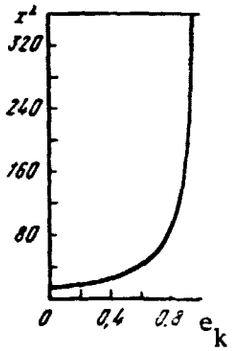


Figure 1

If $r_{\alpha k} < r_{\alpha H}$, it is easy to show that for the ranges of change of parameters of the initial orbits possible in our problems, the optimal transition is a two-burn transition. In order to prove this, we use the results of [4], in which the area of values of the ratio $r_{\alpha k}/r_{\pi H}$ (the subscript π is assigned to the pericentric distance) is established for various values of eccentricity e_k, in which the optimal three-burn apsidal transition is less economical than the optimal two-burn transition. It is proven in [5] that the optimal two-burn transition type I-I passes through an orbit, the apocenter of which agrees with the apocenter of the orbit with the greatest apocentric distance, while the pericenter agrees with the pericenter of another orbit. The optimal preburn transition, with which it is compared, has its first burn at the pericenter of the initial orbit, its second at the apocenter with $r_\alpha = r_{max}$, produced after the first orbital burn, its third -- at the pericenter of the final orbit. Figure 1,

borrowed from [4], presents the dependence of x on e_k, produced under the condition that $r_{\pi k} > r_{\pi H}$, which in our case always occurs. Where $r_{\alpha k}/r_{\pi H} < x$, the three-burn transition requires a higher characteristic velocity than the two-burn transition. Turning to the version of transition II-I with $r_{\alpha k} < r_{\alpha H}$, we see that if eccentricity e_k is such that $r_{\alpha k}/r_{\pi H} \leq x$, the two-pulse transition is more economical in this case as well. Actually, the expenditures of characteristic velocity with a two-burn transition II-I are the same as in case I-I, while the expenditures with a three-burn transition II-I are greater than for I-I, which follows from a theorem of [6], according to which for the optimal transition we must impart apsidal impulses if this is permitted by the limitations.

Calculations performed for a broad class of possible trajectories of transition to orbits around Mars and Venus have shown that the relationship between e_k and $r_{\alpha k}/r_{\pi H}$ are such that always $r_{\alpha k}/r_{\pi H} < x$, i.e., a two-burn transition is optimal. It is obvious that among all possible orbits H with a given value of $r_{\alpha H}$, in which the spacecraft is transferred as a result of deceleration in the atmosphere, the optimal is that for which $r_{\pi H} = r_{\pi H max}$. This results from the fact that the first burn is minimal where $r_{\pi H} = r_{\pi H max}$, while the second, with fixed $r_{\alpha H}$, is independent of $r_{\pi H}$.

Suppose now $r_{\alpha H} < r_{\alpha k}$. Then, as has been noted, the transition from orbit H to orbit k is either a two-burn transition with the first burn at the intersection of orbit H with the boundary of the atmosphere and the second at the apocenter of orbit k, which corresponds to the apocenter of the transition orbit, or a three-burn transition with the first burn at the same point, at the pericenter of orbit k. The value of the third burn, obviously, is independent of the parameters of the initial orbit H.

Let us now prove that the sum of the first two burns decreases with increasing height of the pericenter of orbit H if the height of the apocenter of orbit H is fixed.

Let us represent $1/r_\alpha = S_\alpha$. We assume, without thereby limiting generality, the gravitational constant of the planet $\mu = 1$ and the distance of the boundary of the atmosphere from the center of the planet $r_{min} = 1$. We produce the relationship between the projections of velocity v on the radius vector of

/145

the apparatus from the center of the planet and a perpendicular to the radius vector. These projections are represented by v_r and v_n respectively, while the relationship between them will be produced for the quantity $r = r_{min} = 1$ for all orbits having $r_\alpha = 1/S_\alpha$. Since the equation for the energy integral can be written as $(v_n^2 + v_r^2/2) - 1 = (v_\alpha^2/2) - S_\alpha$, while the equation for the kinetic moment $v_\alpha r_\alpha = v_n$, then for v_n and v_r we obtain the relationship $(v_n^2/2)(1 - S_\alpha^2) + (v_r^2/2) = 1 - S_\alpha$. Since $S_\alpha < 1$, this last equation in coordinate system v_n, v_r is the equation of an ellipse with semimajor axis $a = \sqrt{2/(1 + S_\alpha)}$, semiminor axis $b = \sqrt{2(1 - S_\alpha)}$ and eccentricity $e = S_\alpha$.

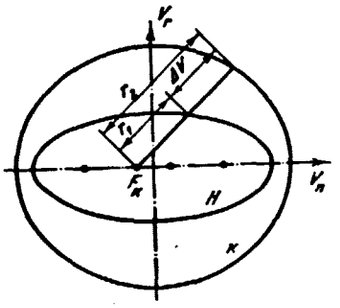


Figure 2

According to our assumption $S_{\alpha H} > S_{\alpha k}$; therefore, $a_H < a_k$, $b_H < b_k$; the corresponding ellipses are shown in Figure 2.

As follows from [3], with optimal transfer from orbit H to orbit k, the first burn in the coordinate system v_n, v_r is directed along a straight line passing through the focus of the ellipse k and the point on ellipse H determined by the values of v_n, v_r, at the intersection of the initial orbit with the circle $r = r_{min}$. Let us represent the distance from the focus f_k of ellipse k to the intersection of the straight line mentioned above with ellipse k as r_2 and use r_1 to represent the distance to the intersection with ellipse H. Obviously, the value of the first burn then can be expressed as $\Delta v_1 = r_2 - r_1$. We must prove that

$$\frac{d(\Delta v_1 - \Delta v_2)}{dr_{nH}} < 0 \qquad \text{where} \qquad r_{nH} < 1,\ S_{nH} > S_{nk},\ v_n \geqslant 0.$$

It is not difficult to see that

$$\frac{dr_{nH}}{dv_n} > 0 \quad (S_\alpha = \text{const}).$$

Since with increasing v_{nH}, the value of v_{nk} also increases, an increase in $r_{\pi H}$ results, with the optimal transition, in an increase in $r_{\pi k}$. Therefore

$$\frac{d\Delta v_2}{dr_{\pi H}} < 0.$$

We can prove our statement by establishing that

$$\frac{d\Delta v_1}{dr_{\pi H}} < 0$$

or, which amounts to the same thing,

$$\frac{d(r_2 - r_1)}{dv_{nH}} < 0.$$

The proof is achieved by simple construction of the function $f(S_{\alpha H}, S_{\alpha k}) = d(r_2 - r_1)/dv_{nH}$ in the area $0 < S_{\alpha H} < 1$, $0 < S_{\alpha k} < S_{\alpha H}$.

Thus, if the control of the motion of the spacecraft in the atmosphere is optimal and the apocentric distance of the orbit at departure from the atmosphere is $r_{\alpha H}$, then among all controls transferring the spacecraft to an orbit with this $r_{\alpha H}$, the optimal is that which achieves the maximum of $r_{\pi}H$. /146

The structure of this control is established in [7]. In [7], the requirement was set of sufficient smallness of the angle of inclination of the trajectory to the local horizon θ to assume $\sin\theta \approx \theta$, while $\cos\theta \approx 1$. Furthermore, it was assumed that the velocity upon departure from the atmosphere was no less than the circular velocity. Under these conditions for a central field of gravity of a spherical planet with a nonrotating atmosphere with density arbitrarily decreasing with increasing altitude, it was demonstrated that the control which was achieved by changing aerodynamic quality was a relay-type control with not more than one switch.

Calculations performed later for cases when the assumption of smallness of θ was incorrect, while the velocity at the point of departure from the atmosphere was less than circular, showed that the conclusion concerning the structure of optimal control nevertheless remains in force; switching occurs from the maximum value of aerodynamic quality to the minimum value.

Based on what we have said, it is easy to construct an algorithm for calculation of the optimal control and the corresponding trajectory for transfer from the assigned hyperbolic trajectory to the orbit of the satellite with assigned apocentric and pericentric distances.

The algorithm is reduced to solution of the extremal problem of search for the minimum:

$$\min_{r_{min} \leq r_{\alpha H} \leq r_{max}} \sum_i \Delta v_i (r_{\alpha H}).$$

Here, $\sum_i \Delta v_i (r_{\alpha H})$ is calculated for the optimal control shifting the vehicle, with assigned initial parameters of motion upon entry into the atmosphere, to a trajectory having at exit from the atmosphere the apocentric distance $r_{\alpha H}$. Since the optimal control has no more than one switching point, the quantity $r_{\alpha H}$ and switching time τ are mutually unambiguously related and, consequently, the initial extreme problem is reduced to the simpler (in the computational aspect) problem of defining

$$\min_{r_{min} \leq r_{\alpha H} \leq r_{max}} \sum_i \Delta v_i (\tau).$$

Let us use the result produced to maximize the width of the entry corridor into the atmosphere of a planet with a limitation on the characteristic velocity, suddenly expended in the sector of the trajectory of transition to the satellite orbit, outside the atmosphere.

By width of entry corridor, we mean the length of the interval of values $r_{\pi en}$, for which is it possible to transfer the spacecraft to the required orbit with the limitations assigned.

Calculations confirm the fact, understandable from physical considerations, of the increase in the characteristic velocity necessary to transfer the spacecraft from an assigned satellite orbit with a decrease in the arbitrary pericenter of the flight trajectory $r_{\pi en}$, if $r_{\pi en}$ is less than a certain quantity. Therefore, unless a transition is made to other limitations, the lower boundary of the entry corridor is determined by the available characteristic velocity. Obviously, the minimum value of $r_{\pi en}$ is achieved if control is optimal in the sense of the

minimum sum of velocity changes imparted to the vehicle, while the value of this minimum is equal to the available characteristic velocity. Thus, to determine the lower boundary we must solve the equation for one variable $r_{\pi en}$: /147

$$\min_{\tau} \sum_{i} \Delta v_i(\tau_i, r_{\pi en}) = v_s, \quad r_{\min} \leqslant r_{\alpha H} \leqslant r_{\max},$$

where v_s is the available characteristic velocity.

If the problem is to transfer the spacecraft to a satellite orbit with a fixed value of $r_{\pi k}$, while $r_{\alpha k}$ is any value satisfying the condition $r_{min} \leq r_{\alpha k} \leq r_{max}$, the number of burns after departure from the atmosphere i = 1, and this burn Δv_1 is apsidal at the apocenter of orbit H.

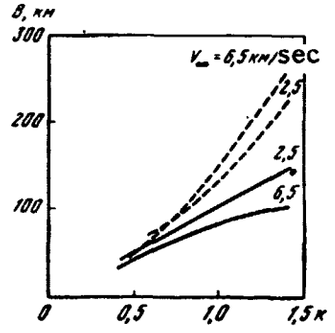


Figure 3

Estimation of the effectiveness of the optimal control was undertaken by solution of just this problem. The parameters of motion were determined by numerical integration. Figure 3 shows the results of calculations for determination of the width of the entry corridor for transfer of the spacecraft to an orbit around Mars. The width of the corridor B was determined as a function of the maximum aerodynamic quality k. It was assumed that the minimum aerodynamic quality $k_{min} = -k$. The graph of the function B = B(k) was constructed for two values of velocity at infinite v_∞ relative to the planet v_∞ = 2.5; 6.5 km/sec. These approach velocities correspond to transfer trajectories in the area of the optimal value as to speed of departure from the Earth. The lower boundary of the entry corridor was determined for a value of available characteristic velocity v_s = 0.2 km/sec. As the upper boundary we took a value of $r_{\pi en}$, for which with k = const the apocentric distance after passage through the atmosphere was 87,580 km, corresponding to an orbit with a period of about 1.05 days.

In the calculations, we used an atmospheric model of maximum density [8]. The solid lines show the dependences $r_{\pi en}(k)$ for flight trajectories in the atmosphere with constant aerodynamic quality $k_{max} = k$, the dotted lines -- for trajectories with the optimal control with a value of $r_{\pi en}$ equal to the

lower boundary of the entry corridor.

As we can see from the graphs, where k = 0.5 and v_∞ = 6.5 km/sec, the optimal control allows us to expand the entry corridor where v_s = 0.2 km/s by approximately 8 km, where k = 1 by approximately 64 km by the corresponding reduction in $r_{\pi en}$. As k increases, the effectiveness of optimal control increases. Thus, where v_∞ = 6.5 km/sec due to the optimal control, the entry corridor for k = 1 increases by 78% of the width of the corridor for a flight with constant quality. Where k = 1.4, the width of the corridor increases by a factor of more than 2.5

In conclusion, the author expresses his gratitude to P. Ye. El'yasberg and V. V. Ivashkin for their useful advice.

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ANALYSIS OF TRAJECTORIES AND PARAMETERS OF A VEHICLE WITH LIMITED ENGINE POWER BY THE METHOD OF TRANSPORTING TRAJECTORIES

M. S. Konstantinov

In his works, F. A. Tsander attached great significance to the investigation of prospective engines. In these investigations, the entire range of problems arising upon selection of parameters of the apparatus and its trajectories is studied. In particular, trajectories are analyzed allowing the target planet to be reached with minimal expenditures [1, pp. 816, 848]. Analysis of trajectories and parameters of a vehicle with an engine of limited power and their optimization are the subject of the present report.

Statement of the problem. In this work, we study the problem of determination of the weight of a power plant, the weight of the working fluid for the engines, determination of the maximum power of the power plant and the program for direction of the thrust vector to provide for performance of a maneuver assigned in a central field of gravity with the maximum payload with fixed initial weight of the spacecraft. It is assumed that the spacecraft consists of the payload, working fluid for the engines and power plant; it is assumed that the engine has limited power and is ideally regulated [2].

The system of equations describing the motion of the spacecraft in a central field of gravity, the gravitational constant of which is k, with angular range θ as an independent variable has the following form:

$$\begin{aligned}
\frac{dr}{d\theta} &= \frac{ru}{V},\\
\frac{dz}{d\theta} &= \frac{rW}{V},\\
\frac{du}{d\theta} &= V - \frac{kr^2}{(r^2+z^2)^{3/2}V} + f\frac{r}{V},\\
\frac{dW}{d\theta} &= -\frac{krz}{(r^2+z^2)^{3/2}V} + h\frac{r}{V},\\
\frac{dV}{d\theta} &= -u + g\frac{r}{V}.
\end{aligned} \tag{1}$$

where θ, r, z are the cylindrical coordinates of the vehicle; u, V, W are the components of the velocity of the vehicle; f, g, h are the components of reactive acceleration. /149

The variables θ, r, z, u, V, W will be called the phase coordinates of the vehicle (their combination will be represented by the vector y, of dimensionality n_1); f, g, h are the controls of the apparatus (vector u of dimensionality k_1); let us introduce the vector of selected parameters γ of dimensionality r_1, which includes, for example the mass of the power plant. System (1) is written in general form as

$$\frac{dy}{d\theta} = f(\theta, y, u, \gamma). \tag{2}$$

Description of the method. The difficulties involved in applying indirect methods of variational calculus to optimal planning of a flight vehicle are easily overcome if the equations of (2) are linear with respect to y. In this case, the boundary problem is solved without iterations.

In order to utilize the idea of linearization, we must select a reference phase trajectory of the flight vehicle to provide the required accuracy of solution of the problem. Determination of the reference trajectory is undertaken using the well developed methods of mathematical programming. Thus, in order to solve the problem of optimization, we develop a combination of direct and indirect methods for solution of the variational problem.

Let us select a control as a function of coordinates y, control parameters γ and the vector of arbitrary parameters a of dimensionality m_1: $u_0(y_0, \gamma, a, \theta)$. We shall refer to control u_0 as the reference control.

The phase trajectory corresponding to this equation depends on $m_1 + n_1$ arbitrary constants. We shall call it the reference or transporting trajectory [3, 4]. If m_1 is sufficiently great, the arbitrary constants may be satisfactory: 1) to satisfy the boundary conditions; 2) to bring the transport trajectory close to the optimal trajectory. The solution of the problem of optimal control relative to the new phase variables $\bar{y}(\bar{y}(\theta)) = y(\theta) - y_0(\theta))$ in the linear relationships relative to $\bar{y}$:

$$\frac{d\bar{y}}{d\theta} = \frac{\partial f(\theta, y_0, u_0(y_0, \gamma, a, \theta), \gamma)}{\partial y_0}\bar{y} + f(y_0, u, \gamma, \theta) - f(y_0, u_0(y_0, \gamma, a, \theta), \gamma, \theta) \tag{3}$$

allows us to refine the solution produced in the class of transport trajectories.

If the reference control rule is selected so successfully that the n_1 independent first integrals of the reference trajectory are known, i.e.,

$$\Psi_i(y_0, \gamma, a, \theta) = C_i \quad (i = 1, \ldots, n_1), \tag{4}$$

then the first integrals of the homogeneous system corresponding to (3) are written as

$$\frac{\partial \Psi_i}{\partial y_0} \bar{y}_{\text{hon}} = D_i, \tag{5}$$

where C_i and D_i are the integration constants.

Independence of the first integrals indicates that the Jacobian $\frac{D(\Psi_1, \ldots, \Psi_{n_1})}{D(y_{10}, \ldots, y_{n_1})}$ is not equal to zero. Therefore, (5) can give us the solution to the homogeneous system (as a function of the constants D_i, coordinates of the transport trajectory and vector of parameters a) and, for example, by the method of variation of arbitrary constants we can find the solution to the heterogeneous system, at least in quadratures.

The solution of the problem of optimal control with linear connections, the integrals of which are known, is found using the maximum principle of [5]. Here, a conjugate system corresponding to (3) is written as /150

$$\frac{d\lambda}{d\theta} = \frac{\partial f(\theta, y_0, u_0(y_0, \gamma, a, \theta), \gamma)^*}{\partial y_0} \lambda. \tag{6}$$

If we know the first integrals of (4), system (6) is easily integrated and its solution is

$$\lambda = \sum_{i=1}^{n_1} \alpha_i \frac{\partial \Psi_i}{\partial y_0}, \tag{7}$$

where α_i are the integration constants of the conjugate system.

Since the connections to $\bar{y}$ are linear, the conjugate system includes neither the control nor $\bar{y}$, i.e., (7) gives us the dependence of the vector of conjugate coordinates λ on the reference trajectory and constants α_i. After determination of the control from the maximum principles as a function of λ and $\bar{y}$, it remains to determine the integration constants from the boundary conditions and the conditions of transversality.

Introduction of the class of transport trajectories. The class of transport trajectories is selected as the set of trajectories consisting of a certain number of sectors (N), in each of which the components of reactive acceleration f_0^i, g_0^i, h_0^i change according to the following rules:

$$f_0^i = \frac{kr_0^i}{(r_0^{i2} - z_0^{i2})^{3/2}} - \frac{k - b^i}{r_0^{i2}} + \frac{a^i u_0^i V_0^i}{2r_0^i},$$

$$g_0^i = \frac{a^i V_0^{i2}}{2r_0^i},$$

$$h_0^i = \frac{kz_0^i}{(r_0^{i2} + z_0^{i2})^{3/2}} + \frac{W_0^i V_0^i}{r_0^i}\left(2a^i - 2\frac{u_0^i}{V_0^i} + d_i\right) + \frac{V^{i2}}{r_0^i}(\gamma_{100}^i + \gamma_{110}^i u_0^i + \gamma_{101}^i V_0^i), \tag{8}$$

where the superscript i represents membership of the phase variables, as well as the introduced constants of the control a^i, b^i, d^i, γ_{00}^i, γ_{10}^i, γ_{01}^i in the ith sector of the trajectory.

The system of connecting equations with the control rules selected is integrated, and its solution can be written as

$$r_0^i = \frac{l^{i2} e^{a^i \theta}}{A^i},$$

$$z_0^i = \frac{S^i l^{i2} e^{(2a^i + d^i)\theta}}{\frac{3}{2}a^i + d^i} - \frac{2\gamma_{100}^i l^i \sqrt{e^{a^i \theta}}}{a^i (a^i + d^i)} - \frac{(\gamma_{10}^i e^{a^i} + \gamma_{01}^i)(k - b^i)\theta}{(a^{i2} + 1)\left(\frac{3}{2}a^i + d^i\right)} +$$

$$+ \frac{k - b^i}{(a^{i2} + 1)\left[\left(\frac{a^i}{2} + d^i\right)^2 + 1\right]}\left\{\left(\frac{B^i}{k - b^i} - \frac{a^i}{a^{i2} + 1}\right)\left[\gamma_{00}^i\left(a^i \frac{1}{2} - d^i\right) - \right.\right.$$

$$\left. - \gamma_{01}^i\left(\frac{a^{i2}}{2} + a^i d^i + 1\right)\right] + \left(\frac{A^i}{k - b^i} - \frac{1}{a^{i2} + 1}\right)\left[-\gamma_{10}^i\left(a^i \frac{1}{2} - d^i\right) - \right.$$

$$\left.\left. - \gamma_{01}\left(\frac{a^{i2}}{2} + a^i d^i + 1\right)\right]\right\} + p^i l^{i3},$$

$$u_0^i = \frac{B^i}{l^i \sqrt{e^{a^i \theta}}},$$

$$V_0^i = \frac{A^i}{l^i \sqrt{e^{a^i\theta}}},$$

$$W_0^i = A^{i2} e^{a^i\theta} \left\{ -\frac{\gamma_{10}^i e^{-a^i\theta}}{l^{i2}(a^{i2}+d^{i2})} - \frac{(\gamma_{10}^i a^i + \gamma_{01}^i)(k-b^i)}{(a^{i2}+1)\left(\frac{3}{2}a^i + d^i\right)} \frac{e^{-\frac{3}{2}a^i\theta}}{l^{i2}} + \right.$$

$$+ \frac{e^{-\frac{1}{2}a^i\theta}}{\left[\left(\frac{a^i}{2}+d^i\right)^2+1\right] l^{i3}} \left\{ \left[\gamma_{01}^i m^i - \gamma_{10}^i n^i - \left(\frac{1}{2}a^i + d^i\right)(\gamma_{01}^i n^i + \gamma_{10}^i m^i) \right] \sin\theta - \right.$$

$$\left. \left. - \left[\gamma_{01}^i n^i + \gamma_{10}^i m^i + \left(\frac{1}{2}a^i + d^i\right)(\gamma_{01}^i m^i - \gamma_{10}^i n^i) \right] \cos\theta \right\} + s^i \right\}. \tag{9}$$

Here l^i, m^i, n^i, s^i and p^i are the integration constants, while A^i, B^i are certain functions:

$$A^i = \frac{k-b^i}{1-a^{i2}} + e^{a^i\theta}(m^i \cos\theta + n^i \sin\theta),$$

$$B^i = \frac{a^i(k-b^i)}{1-a^{i2}} + e^{a^i\theta}(m^i \sin\theta - n^i \cos\theta). \tag{10}$$

The system of independent first integrals is not difficult to produce by solving (9) for the integration constants.

Thus, the transport trajectory selected consists of an arbitrary number of sectors (N), each sector depending on the following 11 constants: five integration constants and 6 control constants. These constants should be used to satisfy the boundary conditions, conditions of continuity of the transporting trajectory and approximation of the transporting trajectory to the optimal trajectory. The number N will be selected from the possibility of such an approximation. The more precisely the solution must be produced, the greater must be N. The constants selected can be considered the points of division of the trajectory into intervals.

Plan for solution of the problem. The problem of search for a transport trajectory with each fixed N is a problem of mathematical programming. This problem was solved using the differential gradient method.

The solution of the linearized problem was undertaken in accordance with the theory presented above. The solution of systems (3) and (6) with the optimal control rule is

$$\bar{y}^i = P^i C^i + R^i k^i + S^i,$$
$$\lambda^i = Q^i C^i + \zeta^i,$$

where C^i and k^i are the vectors of the integration constants; P^i, R^i, S^i, Q^i, ζ^i are matrices defined by the transport trajectory.

From the condition of continuity of phase coordinates $\bar{y}$, we can relate the integration constants by intervals so that constants k^i are defined as a function of a^j, θ_j ($j = 1,\ldots, i$), k^1, $C^{i-1},\ldots, C^1$.

The system of coupling equations in which the problem of optimal control is solved has discontinuities in the right parts upon transition from one interval of the independent variable to another. The necessary conditions for the extreme of the functional for problems with discontinuous right parts [6] indicates continuity of the conjugate coordinates for the present case.

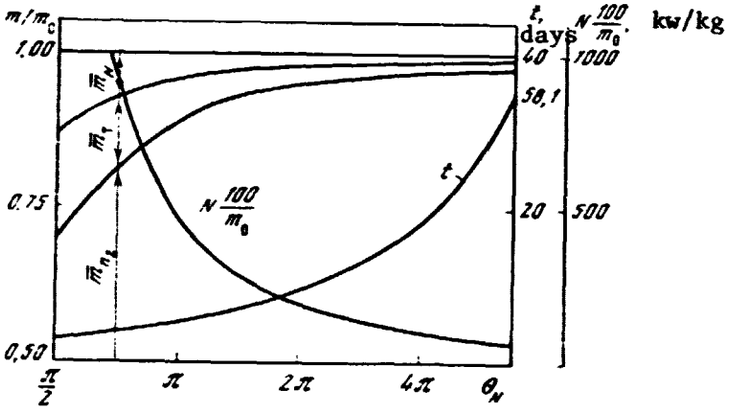


Figure 1

In this case, we can produce C^i as a function of a^j, θ_j ($j = i,\ldots, N$), C^N. Thus, we can select the phase coordinates at any point on the trajectory through the vectors of the constants k^1 and C^N. After this, using the boundary conditions and the conditions of transversality, we can find these constants. We must note that the system of equations relative to the constants can always be made linear, by introducing additional phase variables.

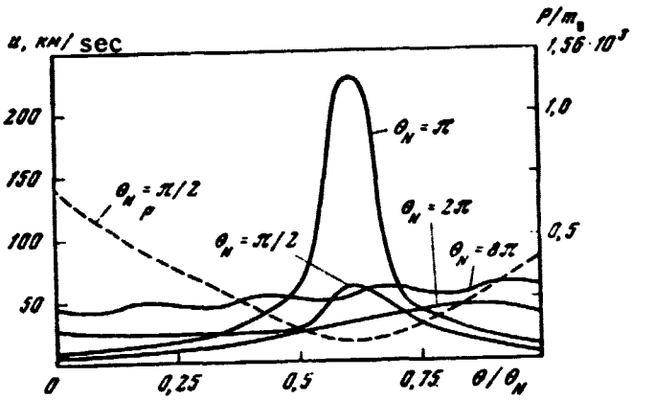


Figure 2

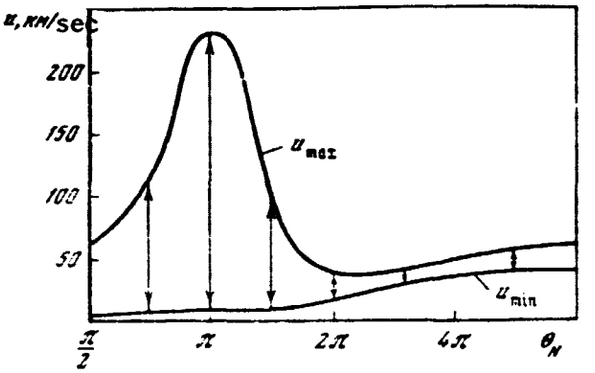


Figure 3

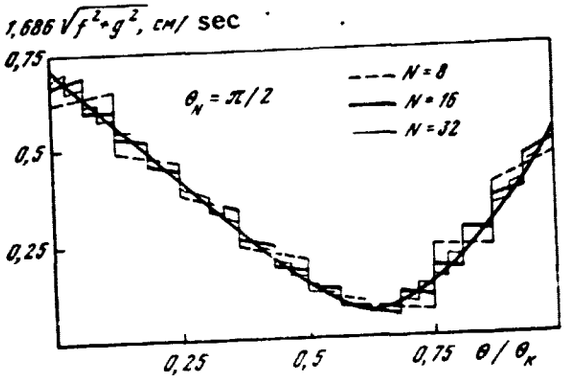


Figure 4

The calculations are performed as follows. The transport trajectory is found with arbitrary, sufficiently small n_0. After this, it is determined once more for number of subdivisions $2N_0$. Then the number of subdivisions is doubled and redoubled until the values of the extremes for various N differ by a sufficiently small quantity ε, selected from the physical essence of the functional. After this, we go over to solution of the second portion of the problem and solve the problem without the additional condition of membership of the trajectory in the class of transport trajectories. If the last solution differs little from the transport trajectory and the boundary and other conditions are satisfied in it with sufficient accuracy, if the difference of functionals in it and in the transport trajectory is less than ε, the problem is considered solved. If any of these conditions is not fulfilled, we must once more increase N. Since the selection at each point of the control constants a^i, b^i,..., d^i represents selection at this point of the components of reaction acceleration, the desired controls, an increase in N can bring the approximation of the transport trajectory arbitrarily close to the optimal (the set of reference controls is always compact in the space of permissible controls).

Analysis of results of calculation. Some results of calculation of the problem of interorbital transfer between coplanar orbits of the Earth and Mars are presented in Figures 1-4.

Figure 1 shows the optimal weight relationships for various angular transfer ranges. We can see the slight gain in relative weight of payload with an increase in angular range for great angular transfer ranges. The optimal transfer time (t) increases significantly. The electric power consumed by the reaction jet decreases with an increase in finite angular range according to a hyperbolic rule.

The optimal rules of change of the reaction acceleration have an oscillating nature. The number of oscillations corresponds precisely to the number of revolutions of the vehicle around the attracting center with high finite angular ranges. The maximum reaction acceleration where $\theta^N > \pi$ decreases with increasing angular range. In the region of angular ranges on the order of π, the maximum required range as to value of reaction acceleration is observed. Figure 2 shows the optimal rules of change of exhaust velocity and thrust of the reaction engine for a large range of finite angular ranges. Figure 3 shows the required ranges of exhaust velocity with a change in finite angular range. A sharp peak in the upper boundary of the required range is noted in the region of ranges $\theta^N = \pi$. The lower boundary of the range increases monotonically.

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Using the suggested algorithm, the results of calculation indicate the possibility of satisfying the boundary conditions with any predetermined accuracy; the rather rapid increase in this accuracy with increasing N (when N is increased by a factor of 2, the accuracy of satisfaction of the boundary conditions increases by a factor of 5); that the increase in finite angular range does not decrease the accuracy of solution of the problem. Refinement of control with increasing N, approximation of the optimal control by the control on the transport trajectory are illustrated by Figure 4.

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THE MOVEMENT OF A SATELLITE IN A KNOWN INERTIAL SYSTEM OF COORDINATES

V. P. Semenko

As we know, F. A. Tsander studied the theory of flight of spacecraft extensively. In spite of the fact that in his investigations he utilized primarily the relationship of Kepler motion, he produced a number of important and interesting results. However, Tsander indicated [1, pp. 285-287] that in many cases, the influence on the movement of spacecraft of such factors as the gravity of the sun and the moon and the influence of the atmosphere must be considered.

At the present time, with increasingly rigid requirements being placed on the accuracy of calculation of the motion of satellites, it is absolutely necessary to consider perturbations in trajectory, the difference between the true and Kepler motion. In this work, we suggest a new approach to the description of the perturbed motion of a spacecraft. /155

We shall study the motion of a satellite of a planet under the influence of a force F. It is considered that force F is the result of the influence of various factors on the satellite, for example the gravitational field of the planet, the atmosphere, the thrust of the engines, etc., and can be arbitrary.

At the center of inertia of the planet, which we consider nonmoving, we place the origin of an inertial Cartesian system of coordinates $0X_0Y_0Z_0$. We introduce the moving system of coordinates OXYZ, the origin of which also coincides with the center of inertia of the planet.

In the noninertial system of coordinates OXYZ, the satellite moves as if it were acted upon by the force

$$\Phi = \mathbf{F} + \{\mathbf{R} \times \omega + 2\mathbf{R} \times \omega + [\omega \times \mathbf{R}] \times \omega\} m, \qquad (1)$$

where ω is the angular velocity of the system of coordinates; R is the vector of the position of the satellite; m is the mass of the satellite.

Force Φ can always be expanded into component Φ_r, colinear with R, and Φ_n, perpendicular to R.

The motion of system xyz relative to the center of inertia of the planet follows the condition

$$\Phi_n = 0. \tag{2}$$

If this condition is fulfilled, in the rotating system of coordinates xyz, the satellite will be acted upon only by the central force Φ_r.

Suppose the rotating system of coordinates (RSC) is selected so that at the initial moment the position vector and local velocity vector of the satellite fall in plane xOy; then the motion of the satellite will obviously always occur in this plane.

Let us write condition (2) in the following form:

$$\begin{aligned}
&\frac{F_{nx}}{m} + y\dot{\omega}_z + \frac{2y\omega_z}{R^2}(x\dot{x} + y\dot{y}) + \frac{y}{R^2}(\omega_y x - \omega_x y)(\omega_x x + y\omega_y) = 0,\\
&\frac{F_{ny}}{m} - x\dot{\omega}_z - \frac{2x\omega_z}{R^2}(x\dot{x} + y\dot{y}) - \frac{x}{R^2}(\omega_y x - y\omega_x)(\omega_x x + y\omega_y) = 0,\\
&\frac{F_{nz}}{m} + x\dot{\omega}_y - y\dot{\omega}_x + 2(\dot{x}\omega_y - \dot{y}\omega_x) - \omega_z(\omega_x x + y\omega_y) = 0.
\end{aligned} \tag{3}$$

Here F_{nx}, F_{ny}, F_{nz} are the projections of components F, orthogonal to R, on the axes of the RSC.

It is not difficult to show that the second equation in system (3) is a result of the first and the condition $F_n \perp R$. As a result of this, the motion of the RSC will actually follow the third equation of system (3) and some one of the first two. The remaining equation (for definition, let us assume it is the second) will obviously be satisfied automatically.

Let us introduce the following symbols:

$$\begin{aligned}
q &= x\omega_y = y\omega_x,\\
p &= x\omega_x - y\omega_y,\\
L &= x\dot{y} - y\dot{x}.
\end{aligned} \tag{4}$$

Then the equations describing the motion of the RSC can be written as

$$\begin{aligned}
&\frac{F_{nx}}{m} + y\dot{\omega}_z + 2\frac{y\omega_z}{R^2}R\dot{R} + \frac{y}{R^2}qp,\\
&\frac{F_{ny}}{m} + \dot{q} + q\frac{\dot{R}}{R} - p\frac{L}{R^2} - \omega_z p = 0.
\end{aligned} \tag{5}$$

It is easy to check that

$$q=-\frac{\lambda_{xy}}{R}, \quad \omega_z=-\frac{\lambda_z}{R^2}, \quad p=0 \tag{6}$$

is a solution of equation system (5).

The variables λ_{xy} and λ_z included in (6) are solutions of the differential equations

$$\lambda_{xy}=\frac{F_{nx}}{m}R, \quad \lambda_z=\frac{F_{ny}}{m}\frac{R^2}{y}. \tag{7}$$

Equality of p to 0 means that the angular velocity vector of the RSC is always orthogonal to the position vector of the satellite.

The components of the angular velocity ω in coordinate system xyz are

$$\begin{aligned}\omega_x&=\frac{\lambda_{xy}y}{R^2},\\ \omega_y&=-\frac{\lambda_{xy}x}{R^2},\\ \omega_z&=-\frac{\lambda_z}{R^2}.\end{aligned} \tag{8}$$

Suppose ν is the angle between the axis OX and the radius vector of the satellite; then the motion of the satellite in plane xOy is described by the equation

$$\begin{aligned}(\ddot{R}-R\dot{\nu}^2)m&=\Phi_r,\\ \frac{d}{dt}(R^2\dot{\nu})&=0.\end{aligned}$$

From the last equation, we immediately produce $R^2\dot{\nu}$ = const. Using (4), we produce $L = R^2\dot{\nu}$ = const.

As a result, the equations of motion of the satellite in the plane of the RSC are

$$\ddot{R}=\frac{L^2}{R^3}=\frac{\Phi_r}{m},$$

$$\dot{\nu}=\frac{L}{R^2}. \tag{9}$$

In order to write the kinematic equations closing (7) and (9), we must select some specific system of angles relating the RSC to the reference system of coordinates.

Suppose the position of the RSC relative to $x_0y_0z_0$ is fixed by means of Euler angles.

We then produce

$$\dot{\theta}=\frac{\lambda_{xy}}{R^2}\sin(\psi+\nu),$$

$$\dot{\varphi}=\frac{\lambda_{xy}}{R^2\sin\theta}\cos(\psi+\nu),$$

$$\dot{\psi}=-\frac{\lambda_z}{R^2}+\frac{\lambda_{xy}}{R^2}\cos(\psi+\nu)\operatorname{ctg}\theta. \tag{10}$$

Combining (7), (9) and (10), we can write the entire system of equations of motion of the satellite and the RSC:

$$\ddot{R}=\frac{L^2}{R^3}+\Phi_r,$$

$$\dot{\nu}=\frac{L}{R^2},$$

$$\dot{\lambda}_{xy}=F_{n_2}R,$$

$$\dot{\lambda}_z=F_z\frac{R}{\sin\nu},$$

$$\dot{\theta}=\frac{\lambda_{xy}}{R^2}\sin(\psi+\nu),$$

$$\dot{\varphi}=-\frac{\lambda_{xy}}{R^2\sin\theta}\cos(\psi+\nu),$$

$$\dot{\psi}=\frac{\lambda_{xy}}{R^2}\cot\theta\cos(\psi+\nu)-\frac{\lambda_z}{R^2}. \tag{11}$$

Here, we assumed m = 1 which, as we can easily see, does not reduce the generality of the equations. In certain cases, it is more convenient to use another form of the equations of motion.

We note first of all that

$$\frac{F_{nz}}{\sin \nu} = F_{nxy},$$

where F_{nxy} is the projection of F_n on plane xOy.

Considering that now in the right portions of the equations ν is encountered only in sum with ψ, let us introduce the new variable $u = \psi + \nu$. Due to the introduction of variable u, the number of equations of the system can be decreased by 1.

We can now write the system of equations in another, more compact form:

$$\begin{aligned} \dot{R} &= \frac{L^2}{R^3} + \Phi_r, & \dot{\theta} &= \frac{\lambda_{xy}}{R} \sin u, \\ \dot{\lambda}_{xy} &= F_{nz} R, & \dot{\varphi} &= -\frac{\lambda_{xy}}{R^2 \sin \theta} \cos u, \\ \dot{\lambda}_z &= F_{nz} \frac{R}{\sin \nu}, & \dot{u} &= \frac{L - \lambda_z}{R^2} - \dot{\varphi} \cos \theta. \end{aligned} \tag{11'}$$

The new form of the equations of motion (11') is preferable in computer calculations.

Let us analyze the systems of equations produced. First of all, we note that systems (11) and (11') are strict, with nothing ignored in their production. The variables of system (11) have simple geometric sense. θ, ϕ, ψ define the position of plane xOy relative to the nonmoving system of coordinates. Variables R and ν define the position of the satellite in plane xOy. L is the specific kinetic moment of the satellite in the RSC.

In order to clarify the sense of variables λ_{xy}, λ_z, let us project the vector of the full kinetic moment L_0 onto the axes of the RSC: $L_{0RSC} = R \times \dot{R}_{loc} + \omega \times R^2$, but /158

$$\mathbf{R} \times \mathbf{R}_{loc} = L = \begin{pmatrix} 0 \\ 0 \\ L \end{pmatrix}.$$

Using (8), we produce

$$L_{ORSC}=\begin{pmatrix} \lambda_{xy}\frac{y}{R} \\ -\lambda_{xy}\frac{x}{R} \\ L-\lambda_z \end{pmatrix}.$$

From this it follows that λ_{xy} is the projection of the vector of kinetic moment of the satellite in the reference system of coordinates L_0 on the moving plane xOy. Variable λ_z us the difference in the projections of vectors L and L_0 on the Oz axis.

It should be noted that, in contrast to the osculating plane or plane xOy of the ideal system of coordinates of Ganzen [2, 3], the plane xOy of the RSC, generally speaking, does not contain the vector of the full velocity of the satellite.

Let us study the systems of equations (11), (11') from the standpoint of their use for computer calculations. In a broad class of practically important problems computer calculations are performed using equations in osculating elements. However, we know that when these equations are used, a number of problems arise. The difficulties appear when the orbit is near circular, when the orbital inclination is slight, when the orbit is near parabolic. Equation systems (11) and (11') do not have these shortcomings; they are quite general and allow effective calculation of orbits of all types with all inclinations.

We note that sin θ in the denominator of the last two equations of systems (11) and (11') does not lead to difficulties. For orbits with any inclination we can always select an initial position of the RSC such that sin θ does not vanish. System (11) actually consists of 7 first order differential equations, while the system of equations in osculating elements consists of 6. Nevertheless, specific computer calculations show that with identical accuracies, system (11') is integrated more rapidly.

Let us now introduce the relationships for transition from the coordinates of position and velocity of the satellite to the reference system of coordinates for elements of system (11).

The coordinates of the satellite in the RSC are determined as follows:

$$\mathbf{R}=\begin{pmatrix} R\times\cos\nu \\ R\times\sin\nu \\ 0 \end{pmatrix}. \qquad (12)$$

The full velocity in the RSC is

$$\dot{\mathbf{R}}=\tilde{\dot{\mathbf{R}}}+\omega\times\mathbf{R}.$$

Here and subsequently, the wavy line marks local derivatives.

Using (8), we produce /159

$$\dot{\mathbf{R}}=\begin{pmatrix} \tilde{\dot{R}}_x-\frac{\dot{\lambda}_z\sin\nu}{R} \\ \tilde{\dot{R}}_y-\frac{\dot{\lambda}_z\cos\nu}{R} \\ \frac{\dot{\lambda}_{xy}}{R} \end{pmatrix}. \qquad (12')$$

Since $\tilde{\dot{R}}_x$ and $\tilde{\dot{R}}_y$ are not directly needed, we go over immediately to V_r and V_n -- the components of local velocity colinear and orthogonal to R

$$\tilde{\dot{R}}_x=V_r\cos\nu-V_n\sin\nu,$$
$$\tilde{\dot{R}}_y=V_r\sin\nu+V_n\cos\nu. \qquad (12'')$$

Here V_r is the projection of the full velocity of the satellite on the radius vector; V_n is determined from the obvious equation $|V_0| = |R_0|$.

Using (12') and (12"), after simple transforms we produce

$$V_r=(\mathbf{R},\mathbf{V})/R,$$
$$V_n=\frac{\dot{\lambda}_z}{R}=\sqrt{V_0^2-V_r^2-\frac{\dot{\lambda}_{xy}^2}{R^2}}. \qquad (13)$$

The fact that V_r does not depend, while V_n does depend on λ_{xy} and λ_z, which define the angular velocity of the RSC, is quite natural. The ambiguity of V_n means in practice that for any R_0, V_0, λ_{xy} and λ_z we can select two positions of the RSC for which the projection of the total velocity on the Oz axis is equal to λ_{xy}/R.

Let us now produce relationships allowing us to determine the position of the RSC relative to coordinate system $x_0y_0z_0$.

Suppose we know the coordinates of the vectors R and V in the reference and rotating systems of coordinates. We must find matrix A such that

$$\mathbf{R}_0 = A\mathbf{R},\ \mathbf{V}_0 = A\mathbf{V}. \tag{14}$$

This task, generally speaking, can be performed by directly using the vector relationships and any three of the known relationships between the elements of the rotation matrix A. However, in this case the system of algebraic equations for determination of the elements of the matrix is nonlinear with all of the difficulties which result.

Let us study another method of determining the elements of matrix A. Let us assume that we are given a third vector W, the coordinates of which are also known both in $x_0y_0z_0$ and in xyz.

From the coordinates of the vectors R, V and W, we formulate the following two matrices:

$$B = \begin{pmatrix} R_{01} & V_{01} & W_{01} \\ R_{02} & V_{02} & W_{02} \\ R_{03} & V_{03} & W_{03} \end{pmatrix}, \qquad C = \begin{pmatrix} R_1 & V_1 & W_1 \\ R_2 & V_2 & W_2 \\ R_3 & V_3 & W_3 \end{pmatrix}.$$

Then obviously B = AC, from which

$$A = BD^{-1}. \tag{14'}$$

Obviously, in order for determination of A to be possible, vectors R, V and W must be linearly independent and not equal

to zero. It is not difficult to show that the matrix A thus produced is orthogonal.

Using the results produced, we can define matrix A from the coordinates of the full velocity vector and the satellite position vector fixed in $X_0Y_0Z_0$ and xyz. /160

The cases V||R and V = 0 are trivial and we will not study them. We note only that in these cases, the position of the RSC can be selected arbitrarily. One natural condition flowing from the production of system (11) is that R belong to plane xoy.

Using the position vector and the vector of the full velocity, let us introduce a third vector $W_0 = [R_0 \times V_0]$; $W_0 = [R \times V]$. If A in (14') is a rotation matrix, we can show that $W_0 = AW$.

Omitting cumbersome transforms, we can write the matrix produced

$$A=\frac{1}{W^2}\begin{pmatrix} x_0p_x+\dot{x}_0q_x+W_{0x}W_x & x_0p_y+\dot{x}_0q_y+W_{0x}W_y & x_0p_z+\dot{x}_0q_z+W_{0x}W_z \\ y_0p_x+\dot{y}_0q_x+W_{0y}W_x & y_0p_y+\dot{y}_0q_y+W_{0y}W_y & y_0p_z+\dot{y}_0q_z+W_{0y}W_z \\ z_0p_x+\dot{z}_0q_x+W_{0z}W_x & z_0p_y+\dot{z}_0q_y+W_{0z}W_y & z_0p_z+\dot{z}_0q_z+W_{0z}W_z \end{pmatrix}, \tag{15}$$

where p = [V x W], q = [W x R].

Matrix A is common and allows us to determine the position xyz related with $X_0Y_0Z_0$ by any system of angles. To do this, the elements of matrix A must be set equal to the corresponding elements of the transition matrix, expressed through angles.

Since the RSC is defined here relative to the reference system of coordinates by Euler angles, rotation matrix D, expressed thrcugh these angles, is as follows [4]

$$D = \begin{pmatrix} \cos\psi\cos\varphi-\cos\vartheta\sin\varphi\sin\psi & -\sin\psi\cos\varphi-\cos\vartheta\sin\varphi\cos\psi & \sin\vartheta\sin\varphi \\ \cos\psi\sin\varphi+\cos\vartheta\cos\varphi\sin\psi & -\sin\psi\sin\varphi+\cos\vartheta\cos\varphi\cos\psi & -\sin\vartheta\cos\varphi \\ \sin\vartheta\sin\psi & \sin\vartheta\cos\psi & \cos\vartheta \end{pmatrix}. \tag{15'}$$

Using this matrix, we produce

$$\cos\theta = a_{33}, \quad \sin\theta = \sqrt{1-a_{33}^2},$$
$$\cos\varphi = -\frac{a_{23}}{\sqrt{1-a_{33}^2}}, \quad \sin\varphi = \frac{a_{13}}{\sqrt{1-a_{33}^2}},$$
$$\cos\psi = \frac{a_{32}}{\sqrt{1-a_{33}^2}}, \quad \sin\psi = \frac{a_{31}}{\sqrt{1-a_{33}^2}}, \tag{16}$$

where a_{ij} are the elements of matrix (15).

Angles θ and ϕ define the position of the moving plane relative to the reference system of coordinates. Angle ψ determines the position of the Ox axis in this plane.

In the right parts of (11), ψ is encountered only together with ν. This is a result of the physically understandable fact that in the moving plane, axes Ox, Oy can be placed arbitrarily.

Using the results produced above, let us study the problem of the initial data for the system of differential equations (11). Suppose at the initial moment we know R_0 and V_0 -- the position and velocity of the satellite in the reference system of coordinates. The problem is to determine at this moment R, V_r, ν, λ_{xy}, λ_x, θ, ϕ, ψ, L.

The value of R is determined obviously, V_r is produced from relationship (13). Considering the arbitrary nature of the initial orientation of the Ox and Oy axes, angle ν can be arbitrary. For definition, let us agree to set the initial value of ν equal to zero. The initial values λ_{xy} and λ_z, defining /161
the initial twist of the RSC, obviously, can also be selected arbitrarily. However, it should be kept in mind that in contrast to ν, selection of λ_{xy} and λ_z influences both the motion of the satellite in the moving plane and the motion of the RSC itself. The initial value of λ_{xy} should satisfy the relationship $|\lambda_{xy}| \leq |R_0 \times V_0|$. This limitation follows from the physical sense of λ_{xy}.

If the initial values of ν, λ_{xy} and λ_z are selected, angles θ, ϕ and ψ are determined by means of (12), (12'), (16) and (15). The constant L encountered in the right parts of equations (11) is determined from the relationship $L = V_n R$.

It should be noted that the ambiguity in the definition of V_n (13) leads with fixed ν, λ_{xy} and λ_z to ambiguity in the definition of the initial values of θ, ϕ, ψ and also L.

These two systems of initial data for (11) have equal rights. Integration with either of the two sets leads to different values of the elements (except, naturally R and V_r). However, if we translate these elements into coordinates and velocities of the satellite in the reference system of coordinates, the results are identical for both systems of initial data.

Let us now study the transition from elements of equation system (11) to the coordinates and velocity of the satellite in the reference system of coordinates. Suppose at a certain moment we know R, V_r, ν, λ_{xy}, λ_z, θ, ϕ, ψ and L. We must determine R_0, V_0 -- the position vector and velocity vector of the satellite in the nonmoving system of coordinates.

First let us define the position vector R and vector of full velocity $\dot{R}$ in the moving system of coordinates. Using formulas (12) and (12'), we produce

$$\mathbf{R} = \begin{pmatrix} R\cos\nu \\ R_0 \sin\nu \end{pmatrix},$$

$$\dot{\mathbf{R}} = \begin{pmatrix} V_r \cos\nu - \frac{L}{R}\sin\nu + \frac{\lambda_z \sin\nu}{R} \\ V_r \sin\nu + \frac{L}{R}\sin\nu - \frac{\lambda_z \cos\nu}{R} \\ \frac{\lambda_{xy}}{R} \end{pmatrix}.$$

Now using the matrices for transition from the RSC to $X_0Y_0Z_0$ (15'), we define R_0 and V_0.

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SLIPPING MODES OF THE SECOND KIND IN PROBLEMS OF OPTIMAL CONTROL OF THE ROTATION OF A SPACECRAFT

K. G. Grigor'yev, A. M. Nikulin and
Yu. B. Popov

Problems of the performance of interplanetary flights by spacecraft, of determining the optimal design parameters of spacecraft and their control were reflected in the works of our remarkable countryman, F. A. Tsander. /162

In solving some problem related to space flight, Tsander also studied the economic aspect, attempting to reduce the cost of realization of his suggested flight versions, estimating the cost of various structural solutions, the duration of space flights, the possibility of utilization of the atmosphere to decrease the consumption of fuel during descent to a planet, and analyzed methods of decreasing the "total cost of the structure" [1].

As we know, the creation of spacecraft has been based on studies primarily related to the creation of a system for the control of the rotation of the spacecraft around its center of mass.

The selection of a specific system for controlling the rotation of a spacecraft, optimal according to some criterion, assumes the possibility of systematic evaluation of various planned versions. This requires the creation of mathematical models of the behavior of such systems and the solution of the corresponding problems of synthesis of the optimal controls. Among these problems, significant place must be given to degenerate variational problems, the solution of which is a slipping optimal mode of the second kind -- the limit of the minimizing sequence, converging in the phase coordinates to a certain limiting value (line of zero approximation), whereas the control has no limit and is a sequence of switchings at a point [2, 3].

The presence in the solutions of a significant number of variational problems of optimal stabilization of spacecraft of these areas of "slipping" is one basic peculiarity of these problems and is independent of the methods used for their solution. Investigation of the possibility of realization of slipping optimal modes of the second kind is therefore of significant practical interest.

1. In [3], a study is made of optimal control of the orientation of the spacecraft in the sense of minimum fuel consumption with unfixed ending time. The following nonlinear fourth

order synthesis problem is solved: for an arbitrary initial angular velocity of the spacecraft, with projection on the coupled axes (x_0, y_0, z_0) and arbitrary initial mass of the spacecraft, find the pair of vector functions (x, y, z, m) and u'_k, u''_k (k = 1, 2, 3) which satisfy the dynamic Euler equations reduced to normal form and the equation for fuel consumption

$$\dot{x} = \alpha yz + b'_1 u'_1 - b''_1 u''_1. \tag{1}$$

$$\dot{y} = -\beta zx + b'_2 u'_2 - b''_2 u''_2. \tag{2}$$

$$\dot{z} = \gamma xy + b'_3 u'_3 - b''_3 u''_3. \tag{3}$$

$$\dot{m} = -u'_1 - u''_1 - u'_2 - u''_2 - u'_3 - u''_3. \tag{4}$$

with the boundary conditions /163

$$x(T) = y(T) = z(T) = 0 \tag{5}$$

minimizing the functional

$$J = -\int_0^T \dot{m}dt, \tag{6}$$

representing the consumption of fuel for the entire process of stabilization.

When there are no control influences ($U'_k = U''_k = 0$, k = 1, 2, 3), the spacecraft performs passive motion around its center of mass.

The final moment in time T is not fixed,

$$\alpha = \frac{B(m) - C(m)}{A(m)}; \quad \beta = \frac{A(m) - C(m)}{B(m)}; \quad \gamma = \frac{A(m) - B(m)}{C(m)}, \tag{7}$$

where A(m), B(m), C(m)[A(m) $\geq$ B(m) $>$ C(m)] are the main moments of inertia of the spacecraft; b'_k, b''_k (k = 1, 2, 3) are positive constants depending on the arm of the control moment, engine characteristics and moments of inertia of the spacecraft; control actions U'_k, U''_k (k = 1, 2, 3) are the flow rates per second of the working fluid (or thrust force) of the kth pair of engines,

$$0 \leqslant U_k' \leqslant U_{k\max}'; \quad 0 \leqslant U_k'' \leqslant U_{k\max}'' \quad (k=1, 2, 3). \tag{8}$$

We consider that the flow rates of fuel per second can change instantaneously from 0 to the maximum values. The letters x_0, y_0, z_0 and x, y, z are the projections of the vector of angular rotation velocity of the spacecraft on the axes of the central ellipsoid of inertia coupled with the vehicle at the initial moment in time and at any instantaneous moment in time respectively; m is the mass of the spacecraft.

The solution of this problem in [3] was produced in the form of parametric synthesis of optimal controls based on the "method of passive integrals" [2] for solution of the Bellman equation. A typical solution of the problem is a single-period slipping mode of the second kind. The Bellman function is defined in explicit form.

2. In our work, the general results of [4] are used to investigate optimal slipping modes of the second kind, produced upon analysis of stabilization of a specific spacecraft with the following characteristics: main moments of inertia $C = 0.575 \cdot 10^5$ kgm·sec^2; $A = 0.285 \cdot 10^6$; $B = 0.262 \cdot 10^6$ kgm·sec^2; the moment of each of the control pairs and the arm of each of the control engines M = 300 kgm; h = 2.5 m; specific fuel impulse I_s = 300 sec; maximum flow rate per second through each pair U_{max} = 0.2 kg/sec.

Using these initial data, we produce the following specific values of the parameters of the problem, presented in [4]:

$$\alpha = 0{,}702; \quad \sqrt{\alpha} = 0{,}835; \quad \beta = 0{,}868; \quad \sqrt{\beta} = 0{,}931; \quad \gamma = 0{,}4; \quad \sqrt{\gamma} = 0{,}632;$$

$$b_1' = b_1'' = b_1 = \frac{g_0 I_{sp}^2 h}{A} = \frac{1}{190} \text{ kg}^{-1}\text{s}^{-1}$$

$$b_2' = b_2'' = b_2 = \frac{g_0 I_{sp}^2 h}{B} = \frac{1}{175} \text{ kg}^{-1}\text{s}^{-1}$$

$$b_3' = b_3'' = b_3 = \frac{g_0 I_{sp}^2 h}{C} = \frac{1}{38} \text{ kg}^{-1}\text{s}^{-1}$$

$$U_{1\max}' = U_{1\max}'' = U_{2\max}' = U_{2\max}'' = U_{3\max}' = U_{3\max}'' = 0{,}2$$

$$\frac{\sqrt{\alpha}}{b_1'} = \frac{\sqrt{\alpha}}{b_1''} = \frac{\sqrt{\alpha}}{b_1} = 158{,}650 \text{ kg·sec},$$

$$\frac{\sqrt{\beta}}{b_2'} = \frac{\sqrt{\beta}}{b_2''} = \frac{\sqrt{\beta}}{b_2} = 162{,}925 \text{ kg·sec},$$

$$\frac{\sqrt{\gamma}}{b_3'} = \frac{\sqrt{\gamma}}{b_3''} = \frac{\sqrt{\gamma}}{b_3} = 24{,}016 \text{ kg·sec}.$$

In [3], a complete classification of solutions is presented as a function of the constants included in the problem (initial conditions, characteristics of pairs, moments of inertia of spacecraft and geometric characteristics of spacecraft). The form of the solution [3] depends on the relationship between the constants $\sqrt{\alpha}/b'_1$; $\sqrt{\alpha}/b''_1$; $\sqrt{\beta}/b'_2$; $\sqrt{\beta}/b''_2$; $\sqrt{\gamma}/b'_3$; $\sqrt{\gamma}/b''_3$ b'_k, b''_k (K = 1, 2, 3) and on the area of phase space in coordinates C_1^2, C_2^2, where C_1^2 and C_2^2 are the first integrals of the passive motion of the spacecraft [3].

In the case in question, the constants satisfy the following relationships:

$$\frac{b'_1}{b''_1}=1; \quad \frac{b'_2}{b''_2}=1; \quad \frac{b'_3}{b''_3}=1;$$

$$\frac{\sqrt{\beta}}{b_2}<\frac{\sqrt{\alpha}}{b_1}+\frac{\sqrt{\gamma}}{b_3}; \quad \frac{\sqrt{\alpha}}{b_3}<2\frac{\sqrt{\beta}}{b_2}; \quad \frac{\sqrt{\alpha}}{b_1}<\frac{\sqrt{\beta}}{b_2}+\frac{\sqrt{\gamma}}{b_3}.$$

Here, as is shown in [3], all phase space in coordinates C_1^2, C_2^2 is divided into two areas: $C_1^2/C_2^2 \geq \alpha/\gamma$ and $C_1^2/C_2^2 \leq \alpha/\sqrt{\gamma}$. In the area $C_1^2/C_2^2 \geq \alpha/\gamma$, stabilization with the couples U''_1, U'_2, U''_2 will be optimal.

The optimal controls for stabilization of the spacecraft in the area $C_1^2/C_2^2 \geq \alpha/\gamma$ are

$$U'_1=U'_3=U'_3=0; \tag{9}$$

$$U''_1=\begin{cases} 0 \text{ where } (y\neq 0)\vee(x<0), \\ 0\leqslant U''_1\leqslant U''_{1\max} \text{ if } (y=0)\wedge(x\geqslant 0); \end{cases} \tag{10}$$

$$U'_2=\begin{cases} 0 \text{ where } (z\neq 0)\vee(y>0), \\ 0\leqslant U'_2\leqslant U'_{2\max} \text{ if } (z=0)\wedge(y\leqslant 0); \end{cases} \tag{11}$$

$$U''_3=\begin{cases} 0 \text{ where } (z\neq 0)\vee(y<0), \\ 0\leqslant U''_2\leqslant U''_{2\max} \text{ if } (z=0)\wedge(y\geqslant 0). \end{cases} \tag{12}$$

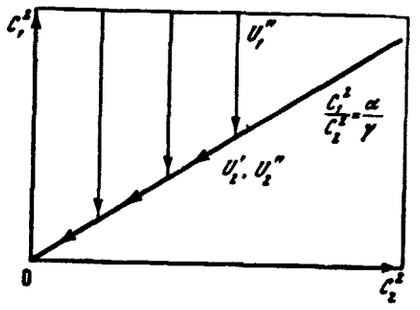
The Bellman function (synthesizing function) is

$$\varphi=-\frac{1}{b_1\sqrt{\beta}}C_1(y,\ x)-\frac{1}{\sqrt{\gamma}}\left(\frac{1}{b_2}-\frac{\sqrt{\alpha}}{\sqrt{\gamma}}\frac{1}{b_1}\right)C_2(y,\ z), \tag{13}$$

where

$$C_1^2(y, x) = \alpha y^2 + \beta x^2, \quad C_2^2(y, z) = \gamma y^2 + \beta z^2. \qquad (14)$$

Conditions (1)-(12) are the conditions of inclusion in a point, corresponding to the sliding optimal mode of the second kind. Using these conditions, we can construct a minimizing sequence, using which functional (6) is made to approach its absolute minimum. This corresponds to the sequence of switchings of pairs U_1'', U_2', U_2'': switching on of pair U_1'' in the small symmetrical vicinity of plane $y = 0$ (10), we shift the phase trajectory to the separatrix $C_1^2/C_2^2 = \alpha/\gamma$; along the separatrix, by switching on U_2' and U_2'' in the small symmetrical areas around plane $z = 0$ (11), (12), we approach the y axis, then following the y axis, switching on pairs U_2' and U_2'', we approach the coordinate origin. The lines of zero closeness of these slipping optimal modes of the second kind are shown on the figure. /165



The results for the area $C_1^2/C_2^2 \leq \alpha/\gamma$ are produced by simple replacement of variables [3].

In [4], we studied the influence of the dimensions of the symmetrical vicinities for switching on the magnitude of additional expenditures of working fluid in comparison to the ideal mode of switching of pairs strictly at the theoretical points [see equations (10)-(12)].

The calculations performed for the case analyzed here show that the functional of the problem is little sensitive to the value of this vicinity. This allows us to realize the slipping modes of the second kind produced at the cost of additional consumption of working fluid by approximately 5-7%.

The optimal mode produced in this work coincides with the mode used to stabilize the Apollo spacecraft, studied in [5].

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OPTIMIZATION OF THE PLAN OF A CLOSED PILOTED FLIGHT OF A VEHICLE WITH AN ENGINE OF LIMITED POWER

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F. A. Tsander turned considerable attention to the investi- /166
gation of promising engine systems. Thus, in the manuscript "The Application of Thin Sheets for Flights in Interplanetary Space," F. A. Tsander in 1924 wrote that for almost all movement within the solar system, extremely slight forces can be used, noting that "...the use of low forces is favored by the possibility of their application over extremely long periods, since flights to other planets are themselves long" [1, p. 362]. The possibility noted by F. A. Tsander of effectively using "low forces" is realized when low-thrust engines are used.

The present work studies the problem of optimization of parameters and trajectories of interplanetary flights of manned spacecraft with such engines and is a continuation of [2].

Manned interplanetary flights with low-thrust engines may possibly require the creation of artificial gravity on board the spacecraft. For this purpose, the vehicle is rotated about its center of mass. If the engine is rigidly attached to the body of the vehicle, the direction of thrust is naturally related to the direction of the axis of rotation and, in order to change the direction of the thrust vector, it is necessary to control the angular motion of the spacecraft by means of controlling moments. However, a rotating vehicle is a gyroscopic system, requiring a significant control moment to turn it (see [2, 3]).

Therefore, for rotating vehicles, we must seek out programs of motion and plan parameters by solution of the variational problem in a new statement considering the motion of the spacecraft relative to its center of mass and the limited nature of the control moments.

It is shown in [2] that the rotating vehicle is a system with a limited angular rate of rotation of the thrust vector, and a new approach is suggested to the optimization of the motion of the rotating spacecraft, in which the vehicle is looked upon as a point of variable mass with limited angular speed of rotation of the control acceleration vector.

Using this approach, let us study the variational problem of optimization of parameters and trajectories of rotating vehicles with a nonregulated engine of limited power.

Formulation of the variational problem. The engine of limited power will be called unregulated if thrust p and exhaust velocity V (and therefore consumption q = p/V) do not change in the process of flight and the controls include only two functions: the on-off switching function $\delta(t)$ and engine reversing function ($\delta = 0$ if the engine is switched off, $\delta = \pm 1$ if the engine is switched on, the change in sign corresponding to thrust reversal) and the angular velocity of rotation of the thrust vector $\bar{\omega}(t)$. The direction of the thrust vector $e(t)(|e(t)| \equiv 1)$ is not a control, but rather a new phase coordinate. The angular rate of rotation of the thrust vector $\bar{\omega}(t)$ is assumed to be an essentially limited quantity (in the case of unlimited ω, we arrive at the traditional statement of the variational problem, analyzed in [4]):

$$|\omega(t)| \leq \omega_* \tag{1}$$

The control system of the angular motion is also considered unregulated, i.e., the angular velocity ω_0 and consumption of the orientation system q_{os} do not change during the process of the flight, and the control includes the on-off switching function $\pi(t)$ ($\pi = 1$ where $\omega = \omega_0$, $\pi = 0$ where $\omega = 0$) and the direction of the angular rate of rotation of the thrust vector $k(t)(|k(t)| \equiv 1)$. /167

A study is made of the problem of seeking out the maximum useful load

$$G_* = G_0 - G_x - G_\mu - G_\omega - G_e \tag{2}$$

with fixed values of launch weight G_0 and time T of performance of an assigned maneuver. The weight of the motor system of limited power G_x is a function of the parameters p and q. The required reserve of working fluid for the sustainer engines

$$G_\mu = gqT_\mu \tag{3}$$

is determined by the consumption q and the total time of operation of the engine T_μ. The entire orientation system of the spacecraft G_ω is a function of the parameters ω_0, q_{os}. The required reserve of working fluid for the orientation system

$$G_\varepsilon = gq_{os}T_\varepsilon \qquad (4)$$

is determined by the consumption q_{os} and the total time of operation of the system T_ε. Therefore, if we fix the parameters P, q, ω_0, q_{os}, regardless of the form of the function $G_x = G_x(P, q)$ and $G_\omega = G_\omega(\omega_0, q_{os})$, the problem is reduced to seeking out the minimum of the linear combination of time T_μ and T_ε:

$$gqT_\mu + gq_{os}T_\varepsilon \to \min \qquad (5)$$

or

$$T_\Sigma = T_\mu + \lambda T_\Sigma \to \min, \qquad (6)$$

where T_Σ is a certain corrected time; λ is the ratio of consumptions of the orientation system and sustainer engines. In this sense, we can speak of the separation of the dynamic portion of the problem.

This variational problem is written in the formulation of Mayer:

$$\begin{aligned}
&\dot{t}_\Sigma = |\delta| + \pi\lambda, \quad t_\Sigma(0) = 0, \quad T_\Sigma = t_\Sigma(T) = \min,\\
&\dot{\mathbf{r}} = \mathbf{V}, \quad \mathbf{r}(0) = \mathbf{r}_0, \quad \mathbf{r}(T) = \mathbf{r}_1,\\
&\dot{\mathbf{V}} = \frac{a_0\delta}{1-\mu t_\Sigma}\mathbf{e} + \mathbf{R}, \quad \mathbf{V}(0) = \mathbf{V}_0, \quad \mathbf{V}(T) = \mathbf{V}_1,\\
&\dot{\mathbf{e}} = \pi\omega_0 k \times e, \quad \mathbf{e}(0) = e_0, \quad \mathbf{e}(T) = \mathbf{e}_1,
\end{aligned} \qquad (7)$$

i.e., we must construct control functions $k(t)(|k(t)| \equiv 1)$, $\delta(t)$ and $\pi(t)$ such that with fixed values of parameters $a_0 = gp/G_0$, $\mu = gq/G_0$, ω_0 and $\lambda = q_{os}/q$ in fixed time T we move from the assigned initial point $\{r_0, v_0, e_0\}$ to the assigned end point $\{r_1, v_1, e_1\}$ with the minimum value of the adjusted time of operation of the sustainer engine and orientation system T_Σ.

It is difficult to produce the solution to the problem in formulation (7) for the limiting case $T_\mu = T_\varepsilon = T$ (no passive sections in the trajectory $\delta(t) = \pm 1$, $\pi(t) = 1$). Here we can use the formulation of the problem for the maximum speed, assuming that

$$T_\Sigma = T \tag{8}$$

If only time T_μ (or T_ε) becomes equal to the time of performance of the maneuver T, in the formulation of the problem in (7) we must assume that

$$T_\Sigma = \min \quad (T_\mu = \min). \tag{9}$$

As a result of the solution of variational problems (7)-(9) for the assigned maneuver $\{r_0, V_0, e_0, r_1, V_1, e_1, R_1 (r, t)\}$ (dynamic portion of general problem) we can produce the dependence

$$T_{\Sigma\min}(a_0, \mu, \omega_0, \lambda, T) \tag{10}$$

of the minimum adjusted time of operation of the sustainer engines and orientation system engines on reaction acceleration a_0, relative consumption of sustainer engines μ, angular speed of thrust vector ω_0, ratio of consumptions of orientation system and sustainer engines λ and maneuver time T.

After this for any type of engine system and angular motion control system (i.e., for any functions $G_x(p, q)$ and $G_\omega(\omega_0, \lambda q)$, we can solve the problem of selecting the optimal plan parameters of the vehicle P, q, ω_0, λ, providing the maximum payload (weight portion of the overall problem). It is reduced to seeking out the minimum of the function

$$\min_{P, q, \omega_0, \lambda} \left\{ G_x(P, q) + G_\omega(\omega_0, \lambda q) + gqT_{\Sigma\min}\left(\frac{gP}{G_0}, \frac{gq}{G_0}, \omega_0, \lambda\right)\right\}. \tag{11}$$

Here, the initial weight G_0 and the time of performance of the maneuver are fixed, while an upper limit may be placed on

the time of operation of the engine. The solution of the weight portion of the problem in this case consists in determining minimum of function (11) with an additional limitation, for example

$$T_{\text{р}} \leqslant \tau, \tag{12}$$

where τ is the operating life of the sustainer engine.

In solving the weight portion of the variational problem, we can consider the weight of the tanks for the working fluid, usually assumed proportional to the initial weight of the working fluid (see [4]). In this case, in place of expression (11) we must use the following expression:

$$\min_{P, q, \omega_0, \lambda} \left\{ G_{\text{к}}(P, q) + G_{\text{дв}}(\omega_0, \lambda q) + (1+\beta) g q T_{\Sigma \text{max}} \left(\frac{gP}{G_0}, \frac{gq}{G_0}, \omega_0, \lambda \right) \right\}, \tag{13}$$

where β is the specific weight of the tanks.

Let us discuss in more detail the possible control systems for angular motion of a rotating vehicle. We can distinguish the following types of systems.

1. Orientation systems using special engines (chemical, electric reaction, etc.), creating only a moment relative to the center of mass. The functional expression of the angular velocity ω_0 through the independent parameters of the vehicle and orientation system in the case of a symmetrical vehicle (regulating characteristic) is

$$\omega_0 = \frac{\sum_{i=1}^{n} P_i l_i}{J_{\text{КА}} \omega_S}, \tag{14}$$

where P_i is the thrust of one engine of the orientation system; n is the number of engines; ℓ_i is the arm of action of the thrust; $J_{\text{КА}}$ is the moment of inertia of the spacecraft relative to the axis of symmetry (axis of rotation); ω_S is the angular velocity of the actual rotation of the vehicle. /169

The weight formula for the orientation system can be reduced to

$$G_{\omega} = G_{\omega}(\omega_0, q_{OS}). \tag{15}$$

2. Orientation systems using matching of the thrust of several sets of sustainer engines placed some distance from the axis of rotation. In this case, the consumption of working fluid not used directly for acceleration of the vehicle is zero, i.e.

$$q_{OS} = \lambda = 0, \tag{16}$$

and in the formulation of the problem (7) we must state that

$$T_{\Sigma} = T_{\Sigma} = \min. \tag{17}$$

The weight component G_{ω} includes the weight of the additional engine units

$$G_{\omega} = (n-1)G_{\gamma}, \tag{18}$$

where n is the number of sustainer engine units; G_{γ} is the weight of one unit.

The regulating characteristic has the form

$$\omega_0 = \varkappa a_0, \tag{19}$$

where

$$\varkappa = \varkappa(n, \mathbf{b}), \tag{20}$$

where the vector of parameters b includes the inertial characteristics of the vehicle, the arms of action of the thrust of the engine units and the kinetic moment of the rotating vehicle.

For this plan of the vehicle, we must provide the condition

$$\varkappa = \max_{\mathbf{b}} \{\varkappa(n, \mathbf{b})\}, \tag{21}$$

where limitations may be placed on the vector of parameters b (for example, structural limitations).

However, parameter n is included in the weight component G_ω and can be defined only by solving the full variational problem. Therefore, using condition (21), we produce

$$x = x(n), \tag{22}$$

and parameter ω_0 is fully defined by a_0 and n from expression (19), i.e., is not independent. The total number of independent parameters becomes equal to 3: $a_0(P)$, $\mu(q)$ and n. They are determined after solution of the dynamic portion of the problem from the condition

$$\min_{P,\,q,\,n}\left\{G_x(P,\ q)+(n-1)G_\gamma(P)+gqT_{p\,\min}\left(\frac{gP}{G_0},\ \frac{gq}{G_0},\ n\right)\right\}. \tag{23}$$

3. The class of orientation systems based on the use of internal control moments resulting from relative movement of parts. An example of the use of such systems in rotating vehicles is presented in [5]. This class includes vehicles with double rotation (the spacecraft consists of two parts rotating in different directions) and orientation systems with a rapidly rotating flywheel located on the axis of rotation of the spacecraft and developing the kinetic moment

$$H_M = H_{KA}. \tag{24}$$

When condition (24) is fulfilled, the motion of the vehicle about its center of mass can be controlled as a nonrotating body, since the total kinetic moment of the spacecraft, obviously, is equal to 0: /170

If the kinetic moment of rotating manned vehicles becomes significant, the weight and angular velocities of such a flywheel also become significant.

Let us make one comment concerning the areas of application of variational problem (7). The following three areas can be distinguished.

Coefficient λ, essentially, characterizes the degree of influence of the angular motion of the vehicle on optimization

of the spacecraft trajectory. Where $\lambda \ll 1$, the expenditures for rotation of the spacecraft are not great and can be ignored, as is usually suggested in spaceflight mechanics for low-thrust situations (see [4]). Where $\lambda \approx 1$, the expenditures for angular motion and acceleration of the center of mass of the vehicle are comparable and the optimal trajectories of the vehicle must be found by solving problem (7). Where $\lambda \gg 1$, the expenditures for rotation of the vehicle become significantly greater than those for acceleration. In this case, trajectories over most of which the condition

$$\varkappa = \omega = 0, \tag{25}$$

is fulfilled become optimal, i.e., the optimal direction of thrust is nearly constant in inertial space.

As the dynamic maneuver in the present case we are considering transfer from the orbit of a satellite of the Earth to the orbit of a satellite of Mars and back. We must solve the problem of selecting the parameters of the rotating vehicle and the control rules with fixed payload weight and an upper limit on total time of the expedition. The optimization is analyzed from the standpoint of the minimum weight of the apparatus in the initial circular orbit around the Earth. The problem of optimization is not divided into the weight and dynamic problems, i.e., both problems are solved simultaneously.

Plan of the transfer. The flight of the vehicle with a low-thrust engine is analyzed using the traditional differentiation between internal and external sections. The entire closed flight consists of a set of four internal and 2 external sections, as well as periods of waiting in orbit around Earth and around Mars. The individual sectors are not joined as to kinematic parameters of the trajectory. All trajectories are considered planar, the orbits of Earth and Mars are considered circular and coplanar. An upper limit is placed on the total time of the expedition, a lower limit on the time spent in orbit around Mars.

Calculation of internal flight sections. In organizing the programmed rotation of the vehicle, the greatest difficulties arise in the internal sections of the flights, which consist of a multiturn spiral around a planet. For the tangential and transversal acceleration programs, as well as the optimal program produced in [6], the vector of reaction acceleration rotates in inertial space with an angular velocity approximately equal to the angular velocity of the orbital motion of the center of mass of the spacecraft. The organization of such acceleration programs requires significant control moments (see [3]). Therefore, the minimum initial weight of the vehicle may be reached

with different acceleration trajectories, occurring with "insufficient" control moment. These trajectories must be sought by solving variational problem (7).

The dynamic maneuver corresponding to the internal sections of the flight is formulated as a problem of achieving the parabolic velocity in the field of gravity of the planet (acceleration sectors) or as the problem of braking upon transition from a parabolic orbit to a satellite orbit (braking section). The systems of equations describing the planar motion are as follows: /171

$$\begin{aligned}
\dot{r} &= V\sin\theta,\\
\dot{V} &= \frac{a_0\delta}{1-\mu t_\Sigma}\cos\alpha - \frac{1}{r^2}\sin\theta,\\
\dot{\theta} &= \frac{a_0\pi}{V(1-\mu t_\Sigma)}\sin\alpha + \left(\frac{V^2}{r}-\frac{1}{r^2}\right)\frac{\cos\theta}{V},\\
\dot{\vartheta} &= \pi\omega_0 + \frac{V\cos\theta}{r},\\
\dot{\varphi} &= V\cos\theta/r,\\
\dot{t}_\Sigma &= |\delta| + \lambda|\pi|.
\end{aligned} \tag{26}$$

where $\alpha = \vartheta - \theta$.

Here R is the radius vector of the center of mass of the apparatus; V is the velocity; θ is the angle of inclination of the trajectory; ϑ is the angle between the thrust and the transversal; α is the angle between the thrust vector and the velocity; ϕ is the polar angle; a_0 and ω_0 are parameters; $\delta(t)$ and $\pi(t)$ are control functions, taking on values of ± 1 and 0.

System (26) is written in dimensionless variables (see [4]).

The boundary condition

$$\begin{aligned}
&t = 0: \quad r = V = 1, \quad \theta = \varphi = 0, \quad \vartheta = \vartheta_0;\\
&t = T: \quad rV^2 = 2, \quad T_\Sigma = \min
\end{aligned} \tag{27}$$

correspond to the problem of zero available energy with the minimal value of adjusted time.

With orientation systems with special engines, the minimizing functional has the form of (6), while the value of parameter λ falls in the area $\lambda >> 1$. Therefore, in connection with the comments made earlier, the optimal direction of the thrust is

close to a constant in inertial space, and condition (25) is fulfilled over a large portion of the trajectory.

Systems of orientation using sustainer engines do not require additional consumption of mass for the creation of control moments (16), but for electric rocket engines ($a_0 = 10^{-3}$-10^{-5} [4]), as was shown in [3], acceptable control moments cannot be produced (see equation (19)). Therefore, such orientation systems are ineffective.

Orientation systems using internal control moments provide tangential, transversal and optimal [6] acceleration programs, but require the presence on board of special systems (flywheels, etc.).

Under these conditions, a system of acceleration of the rotation apparatus with unchanged direction of the thrust vector in inertial space is of practical interest. The functional to be minimized has the form of (17), and condition (25) is fulfilled in the trajectory.

The approximate solution of this variational problem within the framework of the requirement $\delta(t) = \pm 1$, i.e., without switching off the engine in the acceleration sectors (the problem for maximum speed) can be produced using a method suggested in [7] and utilizing the idea of local optimization.

According to this method, the approximately optimal control in the problem with the free end of the trajectory at each moment in time can be determined from the condition /172

$$u_{\text{opt}} = \arg\min_{u}\left[\frac{dF}{dt} + p\frac{d^2F}{dt^2}\right], \tag{28}$$

where F is the minimizing functional, p is a certain parameter.

The derivatives of the functional with respect to time are calculated on the basis of the equations of motion.

Condition (28) and the method of penalty components, reducing this problem to a problem with free right end of the trajectory, allows us to produce an approximate analytic solution of the problem of synthesis of the optimal control as

$$\delta = \operatorname{sign}(\cos\alpha). \tag{29}$$

The derivative of energy with respect to time is always nonnegative in this case.

In solving the problem of interplanetary flight by a nonrotating vehicle, the internal portions are calculated by formulas produced in [6] by processing the numerical results of solution of the problem of achievement of zero energy with unlimited angular velocity of the thrust vector. Analysis of numerical integration of trajectories of acceleration under the influence of thrust in a constant direction with control (29) has shown that the time of acceleration is expressed by the formula

$$T = 1.55\ T_{min}, \tag{30}$$

where T_{min} is the minimum time of acceleration with unlimited angular velocity of the thrust vector, calculated by the formula presented in [6]:

$$T_{min} = \frac{1}{a_0}\left(1 - 0.8209\sqrt[4]{a_0}\left[1 - \frac{\mu}{2a_0}\left(1 - 0.8209\sqrt[4]{a_0}\right)\right]\right). \tag{31}$$

The relative error formula (30) in the range $a_0 = 10^{-3}$-10^{-4} is not over 1%.

Interorbital transfer. The dynamic maneuver on interorbital sections of a flight is formulated as a problem of transfer between circular coplanar orbits of planets in the field of gravity of the sun. The direction of thrust in this case is near constant in inertial space with thrust reversal in the mid portion of the trajectory (see [4, 8]).

As a result, the motion in the field of gravity of the sun is characterized by extremely slight angular velocites of rotation of the thrust vector in inertial space and therefore during calculation of an interorbital transfer, we need not consider the motion of the spacecraft around its center of mass.

Solution of the problem of optimal flight with return. Since we have analytic expression (30) for calculation of the internal sectors, in principle the problem here studied does not differ from the problem of optimization of closed flight of a nonrotating vehicle, the algorithm of solution of which was developed in [8, 9].

According to this algorithm, the problem of optimization of parameters and control rules of the vehicle with an engine of limited power is reduced to a certain problem of mathematical programming by the use of piecewise-continuous approximation of the thrust control rule over the sectors of the interorbital

transfer. The solution of the mathematical programming problem produced is generated using a first order gradient projective method [9].

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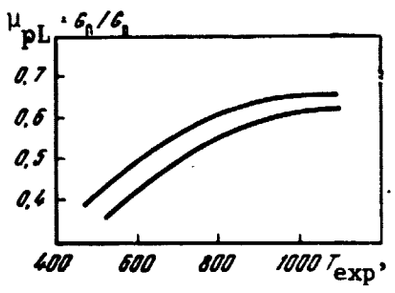


Figure 1

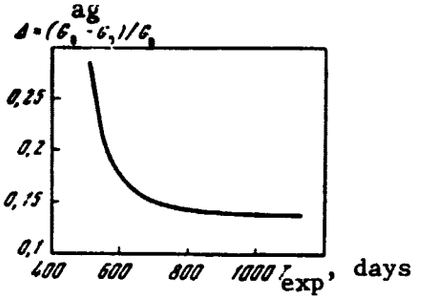


Figure 2

Let us present some calculation results. Of greatest interest is a comparison of the weight characteristics of vehicles with artifical gravity (1) and without it (2) (Figure 1). The reduction in effectiveness of acceleration of a rotating vehicle in the near-planetary areas of motion leads to a decrease in payload. The reduction in payload can be conveniently expressed by the quantity

$$\Delta = \frac{G_0^{ag} - G_0}{G_0}, \qquad (32)$$

where G_0^{ag} and G_0 are the initial weights of vehicles with and without artifical gravity.

The function $\Delta(T_{exp})$ monotonically decreases with an increase in expedition time (Figure 2).

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IV

LIFE SUPPORT SYSTEMS AND ASTROBOTANY

THE WORKS OF F. A. TSANDER IN THE AREA OF THE CREATION OF SPACE LIFE SUPPORT SYSTEMS

G. I. Morozov

Among the many materials of F. A. Tsander on the investigation of problems related to the creation of spacecraft are interesting works on life support systems (LSS). Unfortunately, the overwhelming majority of these materials have not yet been interpreted, preventing us from fully evaluating the heritage of Tsander in this area. /174

An attempt has been made to study and interpret some of the works of Tsander dedicated to life support systems located in the Archives of the Academy of Sciences USSR. Although this investigation is still far from completion, it has yielded some new and, in our opinion, interesting data.

Of great interest are the entries which F. A. Tsander made in his working notebooks, day by day recording his observations and calculations over a period of several years. For example, one of these, notebook No. VI (according to Tsander's own list) [1], contains materials apparently intended for a special book in which Tsander intended to study means of supporting long-term (for several years) human life in a hermetically sealed volume. Among the archive materials in the Tsander collection, this notebook is the most extensive work dedicated to a single problem -- the creation of life support systems. The notebook contains 150 pages of shorthand text written in a very small hand, and 9 6 x 9 photographs, 4 of which are glued to sheets of the notebook, while 5 are attached to the notebook in a separate envelope. Considering that the mean degree of compression of information in shorthand is 4-5, this notebook is equivalent in its volume of information to a book of 600 or 700 pages. Obviously, full interpretation of a text of this size is no simple task. Therefore, we have as yet only a brief review of the contents of the notebook, including interpretation of its name, written on the cover -- "The Possibility of Living for an Unlimited Time in a Hermetically Sealed Volume, Receiving Only Energy from Without."

What are the results produced after preliminary study of Tsander's notebook No. VI? It has been established that Tsander attached great significance to the problem of creating life support systems, noting its important significance in the

problem of supporting space flight. We must note that Tsander made entries in notebook No. VI almost daily from 19 January 1916 through 30 June 1931 with two interruptions, from 22 November 1919 through 9 October 1926 and from 15 April 1927 through 19 April 1930. Thus, the fact that Tsander kept returning to this theme over a period of 15 years, making entries in the same notebook, is of itself remarkable. Analysis of the /175
materials is facilitated by the precision of the entries of F. A. Tsander, who dated all his entries, for many of them even giving the exact time of day.

The serious nature of Tsander's work on LSS is confirmed by the content of the materials in the notebook. The entries were made compact by using shorthand, abundantly accompanied by figures, tables, diagrams and photographs. Thus, on the 150 pages occupied with text (of 154), in addition to explanations and calculations there are figures on 42 pages (130 in all), tables on 60 pages (20 pages are completely filled with tables), graphs and diagrams on 3 pages and 4 photographs.

The attention of Tsander to the problem of creation of LSS is also confirmed by the fact that he returned periodically to several problems, supplementing his entries, adding new figures on the theme at hand -- feeding of plants in space, purification of the water wastes of the crew, methods of preparation of food.

It should be noted that Tsander suggested the construction of life support systems for an interplanetary spacecraft utilizing processes of circulation of substances in the closed volume of the spacecraft cabin, i.e., by recycling the wastes of human vital activity. With this purpose in mind, he theoretically studied several methods of processing. On the very first page of notebook No. VI, in particular, the chemical reaction of CO_2 with an alkali metal (potassium) is studied as a possibility for bonding the carbon dioxide exhaled by the crew.

Tsander studied the possibility of using higher plants in the LSS most completely (including experimentally). His primary task he considered to be not the development of the technology (which he attempted to adapt from terrestrial agricultural technology), but rather the "adaptation of equipment for the conditions of space flight and for the possibility of its use in an interplanetary space ship" [2]. Therefore, his installations for experiments with plants he called prototypes of "aviation weight greenhouses" [3]. As the objects for his experiments, Tsander used radishes, cabbage, lettuce, carrots and even watermelons. The soil was prepared from sand and fecal mass with the addition of certain substances. In his notebooks

are photographs of the plants he grew, drawings and diagrams of systems of soil treatment and irrigation, and notations of the results. In all in the notebook there are 50 special experiments, performed over the course of several months.

Although Tsander's attention was not occupied by the technological, but rather by the basic problems of principle, as a well-educated engineer with a practical bent, during the course of his experiments he looked toward the possibility of further development of his suggestions. This is indicated by the many figures in his notebook [1, pp. 133, 136-139, 146]. Some of these are repeated with design detail, indicating the constant attempts of Tsander toward practical application of his ideas.

We cannot know, but perhaps, given Tsander's developments, biologists might have passed through the stage of hydroponics more rapidly in the investigations of biological LSS or even, perhaps, avoided it entirely. There is no doubt that after full interpretation of notebook No. VI and other Archive materials of Tsander on LSS, we will know many interesting details concerning the works and ideas of Tsander in the area of human life support in space and that these data will be of long use to mankind.

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DEVELOPMENT OF THE IDEAS OF F. A. TSANDER IN THE AREA OF CREATION OF "AVIATION-WEIGHT GREENHOUSES"

V. N. Golobin, V. G. Chuchkin, K. S. Arbuzova and S. Ye. Legkov

In order to support human life during long space flights, /176
K. E. Tsiolkovskiy considered it useful to organize a biological cycle of matter within the spacecraft "similar to that which occurs on the Earth" [1]. For this purpose, he suggested that photosynthesizing higher plants be used, assuming that the plants could simultaneously produce all of the food necessary for the crew, regenerate the water and the atmosphere, and also utilize the physiological wastes of the crew.

Whereas K. E. Tsiolkovskiy limited himself in his works basically to setting the foundation for the possibility in principle of creation of cosmic greenhouses and that which we today call mass transfer calculations, F. A. Tsander turned significant attention to the engineering aspects of the creation of such a system. We have limited information on the creativity of Tsander in this area. We hope that the interpretation of his manuscripts will yield for us new information on the views of this remarkable scientist, who, long before the beginning of specific studies on the development of cosmic greenhouses, predicted the basic characteristics of these devices.

K. E. Tsiolkovskiy and F. A. Tsander considered that the cycle of matter should be an effective means for reducing the weight of supplies necessary for the crew. For this reason, Tsander noted the primary requirement for such a greenhouse -- it must be an "aviation-weight greenhouse." To achieve this, he suggested that the method of "air culture" be used for cultivation of plants, i.e., that the plants be grown "in an empty area," in which the "roots of the plants are simply sprayed with the nutrient fluid. The weight of the entire structure thus produced is very low," he wrote [2].

These statements were made by F. A. Tsander in 1926, i.e., only a few years after the method of "air culture" had been suggested by I. A. Artsikhovskiy for the study of the physiological peculiarities of root systems of plants [3]. It is possible that Tsander was familiar with the works of Artsikhovskiy. Nevertheless, it is Tsander who apparently first suggested that "air culture" be used as a method of growing plants for the production of food products.

The method of "air culture" (or "aeroponics" as it is frequently called today) allows another remarkable idea of Tsander to be realized. He considered that "plants as they grow should be allowed to spread apart without limit, yielding a

savings in space necessary for the greenhouse" [2].

Modern developments have confirmed the correctness of Tsander's opinion, which he set forth some 50 years ago. At the present time, the three main principles of cultivation of higher plants determine the effectiveness of the utilization of greenhouses in the life support systems of extended space expeditions: the aeroponic method of cultivation, spreading of the plants during the process of vegetation and the conveyor method of cultivation, allowing systematic harvesting, with plants of all ages in cultivation.

It is not difficult to see that two of these principles were first set forth by F. A. Tsander.

Calculations have shown that a greenhouse can be profitable, i.e., can actually lead to a reduction in the total weight of stores in a spacecraft, only for long expeditions, and also only if a number of rigid limitations are met. In particular, the greenhouse must have low weight per unit planted area, high radiant energy utilization factor (ratio of energy stored in the growing biomass to the radiant energy striking the plants) and economic value of the harvest (fraction of useful portion in total increase of biomass). Furthermore, cultivation must be intensive, i.e., the radiant flux must be of high power, with a long period of daylight. /177

The greenhouse can be profitable in expeditions lasting no less than 5 years if it meets the following conditions or the values of these parameters:

-- Weight of a unit of planted area, including all supplementary equipment (M_s) not over 25-30 kg/m^2;

-- Radiant energy utilization factor (K_E) at least 7-8%;

-- Economic value factor (K_{ec}) at least 0.6-0.7;

-- Irradiation of plants (E) at least 150 w/m^2 (in the area of the PAR);

-- Duration of daylight (n) at least 18-20 hr/day (average for all crops).

The use of greenhouses in expeditions of shorter duration can be effective if even more rigid requirements are met. For example, with an expedition of two years' length, one must achieve $M_s \leq 25$ kg/m^2, $K_E \geq 10$-12%, $K_{ec} \geq 0.7$-0.8, $E \geq 200$ w/m^2, $n \geq 20$ hr/day. This type of greenhouse could produce 85-90% of the carbohydrates (if sugar is taken in reserve), 40-50% of the

protein, 100% of the vitamins and other physiologically active substances required by man. The plants could also practically completely regenerate the atmosphere and perform primary purification of the water.

Creation of such a greenhouse requires the solution of a number of problems, including:

-- Automatic separation of plants in order to increase the efficiency of utilization of radiant energy and save space and weight;

-- Creation of optimal conditions for light flow to the photosynthesizing organism;

-- Creation of an effective system for automatic regulation of the supply of minerals to the plants in order to reduce the stores of salts and labor required to service the greenhouse;

-- Development of effective "oxygen-free" methods of recovering mineral elements from the nonedible portions of the plants.

At the present time, greenhouses capable of producing the main carbohydrate crops and satisfying the requirements of "aviation-weight greenhouses" have not yet been created, though studies in this direction are under way. For example, we have developed an installation for growing of Chinese cabbage by an aeroponic method with separating conveyor planting of the crops. The plants move from the center toward the periphery in an Archimedes spiral as they grow, assuring high effectiveness of utilization of light energy. The simultaneous spreading of all plants is achieved by rotating the cover of the bath by a certain angle. The installation has been in operation with a few brief interruptions for about a year.

With a planting area of the laboratory cultivator of 0.5 m^2, the harvest as dry weight averages 10 g/day (moist weight 170 g/day). /178

The design harvest (540 g/day) was achieved in preliminary experiments on another installation [4], which may be a prototype of a so-called vitamin greenhouse. This device is not profitable due to the small scale of production. Nevertheless, its inclusion in a life support system for long flights is desirable, since vitamin-rich crops add variety to the diet, improve taste qualities and may have a positive psychological influence on the crew. Furthermore, the operation of small "green" greenhouses in spacecraft may provide the information necessary for the development of effective greenhouses or regeneration of food and air.

Other design solutions of the problem of spreading of plants are known, promising for a carbohydrate greenhouse. This is an extensive field for the activity of engineers and biologists.

Thus, the ideas of F. A. Tsander, which he set forth some 50 years ago on the principle of construction of life support systems of spaceships, particularly the higher plant link, have been reflected and developed in the works of Soviet researchers. Today we are convinced that these principles are basic, and their realization is the quickest path toward creation of an effective greenhouse which can rightfully replace systems involving food storage in long space flights.

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THE DEVELOPMENT OF THE IDEAS OF F. A. TSANDER IN THE AREA OF PROTECTION OF SPACECRAFT FROM ENVIRONMENTAL FACTORS

I. M. Korovin

The assurance of the high reliability of spacecraft at the present time has become one of the most important problems of astronautics. The primary factor determining the reliability of operation of systems and of the spacecraft as a whole with long functioning in space is consideration of the influence of environmental conditions and the taking of steps to protect the spacecraft from these influences.

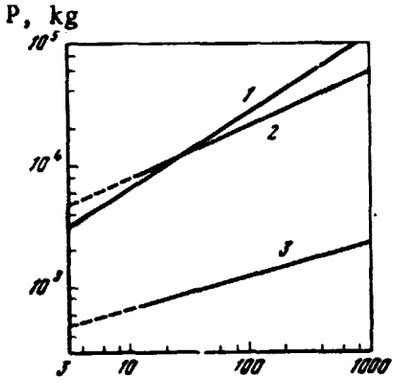
A number of ideas set forth by F. A. Tsander concerning consideration of the effects of certain factors in space have been broadly developed in our own time, though at times with different interpretations. Tsander was the first to suggest /179
the principles of construction of a system for protection from meteoroids using static electricity [1]; he also suggested the use of solenoid wheels to maintain a cloud of charged dust particles, although at the time he intended to use this system as a solar sail [2]; he noted the possibility and usefulness of applying the superconductivity of metals at low temperatures to increase significantly the current passing through the solenoid in creating such systems [3]. The ideas of Tsander at the present time are being developed for the protection of spacecraft from radiation and meteoroid particles; new versions of protection systems are being developed, and the problems which arise upon the creation of such systems are being investigated [4, 5].

Radiation protection. We have now proven the necessity of protecting manned spacecraft from proton radiation. The simplest method of creating radiation protection is to use matter as a shield. However, this leads to a significant increase in the weight of the structure. True, a radiation shelter can be used as protection from the protons which erupt into space during solar flares, allowing the total weight of the protection system to be reduced. This version, however, limits the activity of the crew, the possibility for flight control and the conduct of scientific experiments during solar flares. These limitations can practically eliminate the possibility of a successful expedition if a solar flare occurs during one of the critical phases of the flight. It is therefore clear that we need a radiation protection system which would not influence the normal functioning of the spacecraft and which would be light in weight.

There are two types of pure electrostatic protection. In one plan, first suggested in 1925 by Tsander [1] for protection from charged meteoroid particles, the spacecraft consists of two concentric spheres, imitating the plates of a charged condenser. With this design, the spacecraft as a whole is electrically neutral. However, the creation of a potential, for example of 50 mv, necessary for protection from protons with energies less than 50 MeV, requires a Van de Graaf generator and massive insulators, the weight of which would be greater than the weight of a passive protection system. Furthermore, this system has the same shortcomings as the radiation shelter system. In another plan, the spacecraft is looked upon as a charged condenser with a potential relative to "infinite." However the protons and electrons of the solar wind will discharge the system of its potential in a very short time. The idea of using magnetic fields to protect spacecraft from protons was suggested as the basis of magnetic radiation protection (MRP), the operating principle of which is based on the fact that when charged particles interact with a magnetic field, the source of which is located on board the spacecraft, there is an area of space into which particles of certain energies do not penetrate. These areas are used for the location of the protected sections of the spacecraft. The magnetic field is created by means of superconducting systems cooled with liquid helium. The idea of using superconducting solenoids to create a strong magnetic field on a spacecraft was suggested by Tsander in relationship to a system equivalent to a solar sail and a system allowing acceleration of the spacecraft in the magnetic fields of planets and of the sun [2, 3]. Plasma protection is based on a combination of the principles of electrostatic and magnetic protection; the spacecraft is positively charged and an electron cloud is held at some distance from the spacecraft by a magnetic field which is /180
significantly weaker than the magnetic field required for protection in the case of a purely magnetic system.

In this system, the electric field is directly used for protection from energetic protons, indicating that the electric field potential must be on the order of 30-100 mv for protection from protons with energies of less than 100 MeV. We can determine the geometry of spacecraft with this protection system by noting that the force acting on electrons with charge e moving at velocity V in magnetic field B is e(v x B). From this, the simple requirement for perpendicularity of V x B and B indicates that it is impossible to create a plasma radiation protection shield with spherical symmetry. Therefore, the spacecraft must be topologically similar to a torus.

The concept of plasma protection can be realized if we can solve certain fundamental problems, for example the attainment of superhigh potentials and stable maintenance of an



electron cloud; the problems related to the technical requirements imposed by plasma protection on the system and structure of the spacecraft, for example the selection of the design of the spacecraft, its power plant and leakage control.

Comparison of the weight characteristics of passive (1), magnetic (2) and plasma (3) systems indicates the advantage of the latter for rather large spacecraft (see figure).

However, we must not forget that the final selection of a system must be made in accordance with its possible utilization as protection from other factors of the space environment, for example meteoroid particles.

Meteoroid protection systems. Still more systems have been suggested as protection from meteoroids. In the construction of these systems, such properties of the meteoroid bodies as their mass and the presence of an electrical charge have been considered. Therefore, three types of systems have been studied, protecting spacecraft from uncharged particles, charged particles and artificially charged particles. This last type of system was studied in 1925 by Tsander [1].

The most promising system at present is a protection system using a "dust wall" due to its reliability, low power consumption and low cost. This system is based on the principle of collision of a meteoroid with dust particles made of high density substances (uranium, ozmium) with masses of 10^{-8}-10^{-12} g, artificially maintained near the spacecraft (causing destruction and evaporation of the meteoroid); the distribution density of these particles is 10^3-10^5 particles/m^3, the thickness of the wall is about 1 m. Generally speaking, the necessary parameters of the dust wall will be determined by the physical and mechanical parameters of the meteoroids from which the spacecraft is to be protected. Meteoroids can be classified as follows as to their masses:

-- Particles which can penetrate the hull of the spacecraft, with masses down to 10^{-4}-10^{-6} g; it is desirable to construct bumpers for protection from these particles;

-- Particles which cannot penetrate the hull, with masses of 10^{-6}-10^{-11} g; these particles have an eroding effect on the surface of the spacecraft, but their number is comparatively slight;

-- Particles with masses of 10^{-11}-10^{-14} g, which have a significant eroding effect on spacecraft elements due to their great number. /181

Calculations have shown that all so-called active protection systems (APS) should be used to prevent the eroding influence of very small meteoroid particles.

Returning to the concept of the dust wall, we must note that the primary difficulty is that of maintaining the dust particles near the spacecraft. There are several possible versions of this type of protection. A static dust wall consists of uncharged particles moving parallel to the walls at low speeds (about 0.1 m/sec) between devices which radiate and receive the dust. From the receiver, the dust is once more radiated in the direction of the radiator or is transported within the spacecraft to the radiator. The particles can be accelerated by gas pressure, mechanical acceleration, by forcing liquids (for example, mercury) through small perforations, by evaporation of the dust material from a hot surface. A dynamic dust wall uses charged particles, which move between two electrodes at high potentials at a speed of about 10 m/sec. In evaluating the possibility of using dust wall systems, calculations of their "transparency" were made. It was shown that for a wavelength of 5000 A, a dust wall would be 90% transparent.

More complex is the electrostatic system of maintenance of a dust atmosphere. One version of this system was studied by Tsander, who suggested that loops carrying electric current be used to retain iron powder, electrified by static electricity. This type of system could obviously be constructed using the same principle as plasma radiation protection, using dust particles charged with negative electricity in place of electrons, held near the spacecraft by means of an artifical magnetic field; the body of the spacecraft in this case would be positively charged.

A number of principles of protection from meteoroids can be used if the meteoroid particles carry an electric charge. In [5], it is assumed that at first the meteoroid particles are not charged. They take on a charge as they pass near rods extended from the spacecraft and carrying a high potential (10^6 v). This type of system is effective for meteoroid particles with masses of less than $2 \cdot 10^{-8}$ g. Tsander suggested the use of cathode rays emitted from on board the spacecraft for charging of the meteoroid particles [1].

Some of these suggestions would require great leaps forward in technological development: changing the direction or breaking up large meteoroids, electrostatic reflection of large meteoroids, electric melting and explosion of meteoroids. The weight and power characteristics of various APS are presented in the table.

In our opinion, the most effective systems are those which provide protection from protons and meteoroids simultaneously. We can assume that the meteorite particles, during their long flight through space, take on a positive surface charge due to exposure to hard radiation and friction against the molecules of galactic gas. A surface voltage of 10^{10} v/m would be possible from the standpoint of slight loss of charge to ionic emission. In this case, meteorite particles with masses, for example, of less than 10^{-7} g could be stopped by an electric field with a potential of $1 \cdot 10^{6}$ v. We can conclude from this that a plasma protection system or an electrostatic system maintaining a dust atmosphere, constructed on the principle of plasma protection, might be promising. The former system will provide protection both from protons and from charged meteoroid particles, the latter -- both from protons and from charged and uncharged meteoroid particles. In the case of charged particles, the latter system will stop them both due to collision with the particles of the cloud and due to deceleration in the electric field. Evaluation of the possibilities of combined utilization of such systems requires further development. /183

In conclusion, we must note that the basic principles of these versions of spacecraft protection systems were suggested by Tsander a half century ago, when the very first steps had been just made in the practical creation of rockets, and the theoretical principles of astronautics were just being laid down. Tsander's ideas in the area of protection of spacecraft were ahead even of our time, when modern science and technology has only just begun to approach the practical realization of these ideas.

Principle of Protection	Nature of Protection	Basic Problems	Weight of System, kg	Mass Expended in 1 Year	Power Consumption	Protection from Particles with Mass, g
Passive, protection, bumper	Local partial application	High weight, manufacture of bumpers	7300	None	None	$1.7 \cdot 10^{-4}$
"Dust Wall"	General and local	Maintenance of dust and its transportation	210-370	50-114[1]	100 w	$1.7 \cdot 10^{-4}$[2]
Electrostatic maintenance of dust atmosphere	General	Maintenace of atmosphere. Generation of high potential. Breakdown of vacuum	480	740	Slight	$1.7 \cdot 10^{-4}$
Magnetostatic maintenance of dust atmosphere	Particular location	Maintenance of atmosphere. Light structural material. Weight of superconducting systems, cryogenics. Incomplete shielding	1880[3]	1000	Depends on cryogenics	$1.7 \cdot 10^{-4}$ Only breakup of particles
Change in trajectory, breakup	General	Complexity of system, multiple components, requirement of peak power	1610	1.36	1.1 mw	$1.7 \cdot 10^{-4}$
Electrostatic deflection of particles	Local, partial use[4]	Generation of high potential. Breakdown of vacuum	95/320	None	Slight	$2.10^{-8}/10^{-5}$
Electrostatic deflection of particles	Partial use[4]	"	Depends on length of rod	"	"	$2 \cdot 10^{-7}$ 10^{-4}[5]
Electric melting, explosive pressure	General, local	Generation of high potential uncertainty with vacuum discharge	320-330	"	"	$1.7 \cdot 10^{-4}$[6]

[1]For a spacecraft with a surface area of 400 m^2.

[2]Based on optimistic assumptions.

[3]Dust wall provides no protection from meteoroids with $m \geq m_0$.

[4]General protection only for small meteoroids.

[5]Limited to partial analysis.

[6]Based on optimistic assumptions concerning discharge in vacuum.

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3. F. A. Tsander, "The Problem of Superaviation and Problems of Preparation for Interplanetary Voyages," Problema Poleta pri Pomoshchi Reaktivnykh Apparatov [The Problem of Flight by Means of Reaction Apparatus], Moscow, 1961, pp. 436-441.

4. R. H. Levy, G. S. Janes, "Plasma Radiation Shielding," Space Aeronaut., 1966, 45, 2.

5. C. N. Klahr, N. N. Stein, Active Shielding Against Meteoroids, New York, 1963.

SOME INFORMATION ON THE WRITINGS OF F. A. TSANDER CONCERNING PROBLEMS OF LIFE SUPPORT IN SPACE FLIGHT

G. I. Morozov

Based on the recollections of relatives and contemporaries of F. A. Tsander, we know of his great concern with problems of life support in future space flights, particularly long ones. Tsander, when he still lived in Riga, many times made interesting comments on this problem and even performed independent experimental studies. His system, M. A. Yurgenson-Tsander, recalled [1, p. 207], that he thought about which plants would be best able to cleanse the air in spacecraft cabins, and selected green vegetables with large green areas -- lettuce, cabbage, onions. On the veranda of his home, Tsander conducted experiments on the growing of these vegetables. Apparently, these were the first experimental studies in history on the problem of creation of life support systems. Unfortunately, it is impossible to give any precise date for these works at the present time, since there is no information on them among the deciphered and published materials of Tsander. We can only remark that as early as 1907 Tsander had quite a deep and clear /184 understanding of the functions of a life support system. Thus, in his plain text entry of 10 November 1907, we find, "Problems of construction of spaceship. Conditions determining shape of cabin. Number of outer walls. Compartments... Compressors currently existing. Substances Absorbing CO_2 and other gases produced. Regeneration of oxygen. Processing of wastes: garden in spaceship?... Processing of solar heat" [2].

We can see from this text that at this time the young scientist not only had a rather clear understanding of the problems involved in life support of astronauts on long space flights, but had clearly differentiated between physical-chemical and biological (using today's terminology) life support systems. Thus, he considered it possible to use special substances chemically bonding CO_2 for the absorption of CO_2. He apparently relates the function of regeneration of oxygen to this same group (physical-chemical systems). However, for processing of liquid and solid wastes for the life support of the crew (and also, as can be seen from other sources, for the production of food on board the spacecraft), he preferred to create greenhouses (or "gardens") with various plants.

These and certain other data indicate that Tsander was probably one of the first in the history of astronautics to study the problem of creation of life support systems systematically, expediently and comprehensively. Unfortunately, most of the

Archive materials were written by Tsander in shorthand and have never been interpreted, which makes it difficult to provide a more complete evaluation and analysis of the calculations and experiments. There is no doubt that after the interpretation of the works of Tsander has been completed, we will witness still greater achievements in the solution of the problems of creation of space technology, including life support systems.

In this sense, particularly interesting for us are those materials of Tsander which are wholly dedicated to the investigation of life support systems. Among these, notebook [3], which carries the unique title, "The Possibility of Living for an Unlimited Time Hermetically Sealed, Producing Only Energy from Without" [4][1] is particularly distinguished by its volume and great number of entries.

Unfortunately, this notebook has not been interpreted, and as yet very little is known concerning the nature of the entries in it. Some information has been reported by the author at the first readings in 1970 [5, pp. 82-87]. In this brief report, I will attempt to analyze the dates of the entries in the notebook [3], by comparing these dates with known events from the life of Tsander, as well as the dates of entries in his journal and other notebooks.

First of all, our attention is drawn by the unevenness of entries in the notebook in question both as to frequency and as to volume and nature of text. In all, Tsander made entries in this notebook over a period of 15.5 years (from 19 January 1916 to 30 June 1931), but quite unevenly. Systematic, almost daily entries alternate with time lapses of several months or even years.

It seems possible to distinguish 5 periods of more or less regular entries in the notebook.

The first period -- the initial period of work -- covers the /185
cycle from 19 January 1916 (first entry in the notebook) through 13 May of that same year. These were apparently preparatory entries, preceding the longer and more systematic cycle of special calculations and experimental observations and studies. Our attention is drawn by the significant number of calculations, small figures (as if to confirm his thoughts), sometimes quite tiny, etc. The figures show either individual parts or geometric figures with their dimensions, elements of the soil, etc. In all, 15 figures and 2 tables were made up during this time. The entries during this time are short -- a few lines each.

[1] Notebook [3] [illegible]n shorthand; therefore, its title is quoted according to [4], which mentions the title of this notebook.

Only the first entry covers approximately a page and a quarter, and the entry of 8 February covers approximately 1 page. On 26 February, 25 and 9 March, and 26 April, Tsander wrote but a single line, on 6 March only a half line.

In all, over the 105 days of this period there are 48 entries, covering 18 pages. The entries of this period end with a single line on page 19, after which almost 8 months pass.

The second period of entries Tsander began on 27 December 1916, separating it from the single line of the preceding period by a double black line, leaving almost no blank paper.

This period is the longest, most varied and apparently most significant in the notebook. It continued through 22 October 1919, i.e., almost three years, and contains 253 entries on 88 pages, 36 figures, 30 tables and 4 photographs glued right on to the text.

This section of the notebook is distinguished by its systematic presentation and regular script. If we eliminate a few gaps of a month or so each, easily explained by the distraction of Tsander's attention to other work (which, incidently, is confirmed by comparing the entries in this notebook with other materials, which will be mentioned below), these entries follow each other at intervals of but a day or two. The longest interruptions were: from 6 through 29 January 1917; from 2 December 1917 through 1 January 1918; from 7 January to 4 (17) February 1918; from 17 August through 11 September 1918; from 26 October through 16 November 1918; from 30 November through 9 March 1919 and from 30 March through 30 September 1919.

In spite of the great frequency of these entries, their volume is not great (averaging 0.3 pages). Beginning on 16 July 1917, Tsander indicates not only the day of the week, but also the time (in hours and minutes) of beginning and ending of the entries. These records indicate that on the average an entry took about 1 hour to write (minimum 15 minutes, maximum 3 hours, 20 minutes).

During this time, Tsander prepared space for the description of 50 experiments (on pages 45-61). The results of 44 experiments are described, but the spaces for the results of experiments No. 36, 46-50 remain blank.

The third period of entries begins 6.5 years later, in 1926, and continues for 1 year -- from 9 April 1926 through 15 April 1927. This interruption is probably explained by the fact that the experiments were ended, and also by the fact that at this time Tsander's attention was fully absorbed by problems of the creation of a space rocket.

During the third period, 51 entries were made in the notebook on 31 pages, including 18 tables and 31 figures. At first, the entries were regular, but beginning on 30 June 1926, frequent and long interruptions occurred (entries: 29 July, 19 August, 2 April, 15 April 1927).

The fourth period -- after another three years -- was from 19 April through 18 June 1930. During this time, 23 entries were made on 9 pages (4 tables, 8 figures), many on holidays or the days before holidays.

The last, fifth period, began on 27 September 1929 and /186
includes 12 entries on 4.5 pages. Judging from the preceding dates, at this point Tsander was summing up his many years of observations, which is also indicated by the nature of the entries -- even, smooth, without tables with but one figure.

A comparison of the entries in the notebook [3] with the interpreted journal of Tsander [6] indicates that he made entries on life support systems even on days when he was working very hard on preparation for testing of the OR-1 engine. For example: on 6 October 1930 -- planning of parts for the OR-1 for 6.5 hours. On 9 October -- design of turbine -- 4 hours, planning and design of parts for OR-1 -- 2.5 hours. On 21 October -- calculation of the form of a piston wheel -- 6.5 hours. In the evenings, at home, on these same days there are entries in notebook [3]. The last entry in this notebook was made on 30 June 1931 during his annual month's leave (from 14 June through 13 July).

Of course, more complete conclusions can be drawn after interpretation of the entire Tsander collection, but even a study of the dates allows us to provide some characteristics of the expedient and unusually fruitful activity of Tsander. We can but be amazed at his will power and persistence, which he showed after his hard day's work, returning to his journals and systematically performing calculations, drawing figures, making up tables and writing out explanations. Sometimes Tsander spent 5 to 7 hours in this work. For example, on 13 September 1918 he made entries in one notebook [7] from 11:50 to 12:30, then in another notebook [8] from 6:40 to 7:15 and later in the evening once again in the first notebook from 9:40 to 12:40 -- a total of 6 hours 45 minutes of "straight time" on these three notebooks alone.

Two days later, on 15 September, the picture is repeated: from 9:20 to 10:05 in his second notebook [8] and from 11:05 to 11:15, then from 5:25 to 7:00 in his first notebook [7], and in the evening from 9:30 to 11:00 in the third notebook [3].

Of course, Tsander had periods when he paid more attention to one of his problems, when he simply had no time for his other problems. Obviously, he considered the work on the engine and design of the rocket most important. This we know from many sources, and it is confirmed by the entries in his notebooks. For example, from 1 January through 22 April 1918, Tsander made 87 pages of entries in notebook [7], while his entries on LSS during this time occupy but a single page (12 entries).

This is seen in the interruptions in the entries in the life support notebook from 1927 to 1930 and in the fact that in 1930-1931, these entries were made practically only on holidays.

One very interesting peculiarity of Tsander is his capability to switch rapidly from one work to another -- this is indicated by the times given in his entries: for example, on 20 June 1819, from 7:45 to 2:05, Tsander worked with notebook [7] (engine design), then from 2:20 to 3:50 he wrote in his notebook on life support systems. This indicates his very intense and precisely organized activity.

The saturation of Tsander's working day is also indicated by the entries in his notebook for the same days when he made entries on life support systems.

"17 May 1931:

-- Received permanent pass to TSAGI -- 0.5 hr;

-- Checked drawings for OR-1, etc. -- 2.75 hr;

-- Began calculations for experiment 14 -- 1.5 hr;

-- Conferred on All-Union Conference on Experimental Aerodynamics and studied program -- 1.75 hr;

-- Went to conference -- 1.5 hr; /187

-- Showed V. P. Vetchinkin my instrument and spoke to him concerning my experiments on rockets -- 1 hr.

6 June 1931:

-- Wrote pages 17-18 of experiment 16, drew diagram -- 6.5 hr;

-- Edited pages 60-66 of translation of book of Oberth -- 3.5 hr."

On the whole, the analysis of Tsander's notebook on life support systems shows once more the very intensive, varied and fruitful activity of this talented investigator, one of the pioneers in the creation of space technology.

In conclusion, I would also like to emphasize the great historical and scientific value of the archival materials of Tsander and the pressing need for their interpretation.

REFERENCES

1. Ya. P. Stradyn', "The Riga Period (1887-1915) of the Life and Activity of F. A. Tsander," Iz Istorii Estestvoznaniya i Tekhniki Pribaltiki [The History of Natural Science and Technology of the Baltic Area], Vol. 3, Riga, 1971.

2. F. A. Tsander, "Calculations, Experiments, Comments, Etc.," (Notebook 11), Archives of Academy of Sciences USSR, Folio 573, List 1, File 3, Sheet 79.

3. Archives of Academy of Sciences USSR, Folio 573, List 1, File 13.

4. Archives of Academy of Sciences USSR, Folio 573, List 1, File 216.

5. G. I. Morozov, "The Works of F. A. Tsander in the Area of Creation of Space Life Support Systems," Trudy Pervykh Chteniy, Posvyashchennykh Razrabotki Nauchnogo Naslediya i Razvitiyu Idey F. A. Tsandera [Works of First Readings Dedicated to the Development of the Scientific Heritage and Ideas of F. A. Tsander], Section on "Astrodynamics" and "Life Support and Astrobotany," Moscow-Riga, 1972, pp. 82-87.

6. Archives of Academy of Sciences USSR, p. 4, List 14, File 221.

7. Archives of Academy of Sciences USSR, Folio 573, List 1, File 10.

8. Archives of Academy of Sciences USSR, Folio 573, List 1, File 5.

APPENDICES

BIBLIOGRAPHY ON THE CREATIVITY OF F. A. TSANDER[1]

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Balklav, A. E., "The Role of F. A. Tsander in the Development of Soviet Rocket Technology," Iz Istorii Tekhniki Latviyskoy SSR [From the History of the Technology of the Latvian SSR], Riga, 1959, pp. 103-112.

A study is made of the value of the activity of F. A. Tsander in the area of rocket-space science and technology. An attempt is made at rough systematization of the creative heritage of the scientist, and the importance of the conduct of studies of the works of F. A. Tsander on the theory of space flight is particularly emphasized.

Belov, B. L., "Characteristics of the Creative Style as an Aspect of the Development of the Heritage of Representatives of Scientific and Technical Thought (Analysis of the Creativity of F. A. Tsander)," Iz Istorii Aviatsii i Kosmonavtiki, No. 16, Moscow, 1972, pp. 3-11.

The essence of one possible approach to the development of the creative heritage of representatives of scientific and technical thought is presented. Individual aspects concerning the realization of this approach as applicable to the investigation of the creativity of F. A. Tsander are discussed.

Belov, B. L., "The Problem of Space Flight in the Early Creativity of F. A. Tsander," Iz Istorii Aviatsii i Kosmonavtiki,

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[1]Over the almost 40 years of development of the creative heritage of F. A. Tsander, a tremendous number of publications have appeared, which urgently require systematization.

This bibliography, in contrast to the bibliography published in the scientist's homeland (F. A. Tsander, Bibliografiya [Bibliography], Riga, 1972), is thematic and reflects one trend in the development of the creative heritage of F. A. Tsander, within the framework of which the scientific and technical creativity of the scientist is being analyzed. However, in composing this annotated list of the "research" works on the creativity of F. A. Tsander, we considered it desirable to include some of the individual most characteristic publications related to other trends in the development of the creative heritage of the scientist.

No. 21, Moscow, 1973, pp. 3-17.

Various aspects of the creativity of F. A. Tsander from the period 1908-1912 are analyzed. A discussion is presented of the genesis of the idea of utilization of the metal structures of a rocket as fuel and a number of statements concerning priority are made.

Belov, B. L., "The Characteristics of the Creative Style of F. A. Tsander," Trudy Vtorykh Chteniy F. A. Tsandera [Works of Second F. A. Tsander Readings], Section on "Study of the Scientific Creativity of F. A. Tsander", Moscow, 1974, pp. 61-80.

In addition to presentation of certain methodological considerations concerning the development of the creative heritage of F. A. Tsander, a number of statements are presented and argued characterizing the peculiarities of the activities of the scientist in the area of rocket technology and astronautics.

Belov, B. L., "Problems of the Dynamics of Rocket Flight in the Creativity of F. A. Tsander," Trudy Tret'ikh Chteniy F. A. Tsandera [Works of the Third F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow, 1975, pp. 18-35.

An analysis of the design-theoretical developments of F. A. Tsander on the ballistics of long-range rockets and comparative characterization of the results of investigations of the pioneers of rocket technology on the flight dynamics of ballistic rockets. Comparative evaluations are presented of the results of the studies of F. A. Tsander and the contemporary state of the same problems.

Belov, B. L., "Characteristics of the Results of the Development of the Creative Heritage of F. A. Tsander," Iz Istorii Aviatsii i Kosmonavtiki, No. 25, Moscow, 1975, pp. 26-38.

In accordance with the content and scale of the works of F. A. Tsander, several stages are distinguished in the development of his creative heritage. A brief description is presented of the peculiarities of each stage and certain new trends are noted in the investigation of the active and results aspects of the creativity /189 of the scientist.

Belov, B. L., "Analysis of the Scientific and Technical Creativity of F. A. Tsander in the Area of Rocket Technology," Dissertation, 1975, 193 pages. Author's abstract of the dissertation "Analysis of the Scientific and Technical

Creativity of F. A. Tsander in the Area of Rocket Technology," Moscow, 1975, 18 pages.

This work analyzes the complex of scientific history problems characterizing the creativity of F. A. Tsander in various areas of rocket technology. In addition to the analysis of the results aspect of the creativity of the scientist, a description is presented of the peculiarities of the activity aspect of his creativity and individual methodological considerations are presented concerning the development of the creative heritage of representatives of scientific-technical thought.

Biryukov, Yu. V., "The Design Peculiarities of the Plan of the Interplanetary Spaceship-Aeroplane of F. A. Tsander," Trudy Pervykh Chteniy F. A. Tsandera [Works of the First F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow, Riga, 1972, pp. 32-47.

The basic stages in the works of F. A. Tsander on the creation of his plan for an "interplanetary spaceship-aeroplane" ("ISA"). Various aspects of the creativity of the scientist are studied, related to the development of the ISA plan, and the general solution of the problem of the provision of energy for a manned space flight. The thesis of the fruitfulness and promise of individual statements which found their technical embodiment in the ISA plan is discussed.

Vedeshin, L. A., Samokhvalova, L. G., "Transformation of the Ideas of F. A. Tsander in Contemporary Studies of Periterrestrial Space," Trudy Vtorykh Chteniy F. A. Tsandera [Works of the Second F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow, 1974, pp. 109-116.

A study is made of a combination of problems reflected in the developments of Tsander, the essence of which was determired by the idea of using the mass-energy resources of the atmosphere.

Voronkov, Yu. S., "The Sources of Practical Astronautics," Zemlya i Vselennaya [The Earth and the Universe], Moscow, 1971, No. 2, pp. 56-60.

Individual aspects of the biography and creative activity of F. A. Tsander are discussed. Some works of the scientist are described, as well as individual investigations dedicated to the development of the creative heritage of F. A. Tsander.

Voronkov, Yu. S., "Some Aspects of the Study of the Scientific Heritage of F. A. Tsander," Trudy Pervykh Chteniy F. A. Tsandera [Works of the First F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow-Riga, 1972, pp. 123-128.

Based on critical analysis of the research literature on F. A. Tsander, some individual negative aspects characterizing the current stage of development of the heritage of the scientist are found. A number of basic considerations of a methodological nature are set forth which, in the opinion of the author, must be considered in continuing the historic reconstruction of the creative activity of F. A. Tsander and evaluating its results.

Zil'manovich, D. Ya., Pioner Sovetskogo Raketostroyeniya F. A. Tsander [F. A. Tsander, A Pioneer of Soviet Rocket Building], Moscow, 1966, 190 pp.

The essence of most of the scientific and practical developments of F. A. Tsander in the area of rocket-space science and technology is set forth in popular form. The most important stages in the life and creative biography of the scientist are discussed. The peculiarities of the creative activity of F. A. Tsander are described.

Zil'manovich, D. Ya., Fridrikh Tsander. Detstvo. Yunost'. Pervyye Issledovaniya [Fridrikh Tsander. Childhood. Youth. First Investigations], Riga, 1967, 202 pp.

The early stage in the life and creativity of F. A. Tsander is discussed and the conditions under which his creative individuality was formed are described.

Klychnikov, Yu. V., "Some Preliminary Results from the Interpretation of the Manuscripts of F. A. Tsander," Trudy Pervykh Chteniy F. A. Tsandera [Works of the First F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow-Riga, 1972, pp. 129-137.

An annotation is presented of individual fragments of the shorthand manuscripts of F. A. Tsander relating to 1905-1933. Based on extensive historiographic work, the author refines and for the first time sets forth certain statements characterizing the priority aspects of the activity of the scientist.

Klychnikov, Yu. V., "New Results from the Interpretation of the Manuscripts of F. A. Tsander," Trudy Vtorykh Chteniy F. A. Tsandera [Works of the Second F. A. Tsander

Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow, 1974, pp. 81-87.

Brief annotations are presented from new interpretations of the shorthand records of F. A. Tsander related to various periods of his activity.

Klychnikov, Yu. V., "Analysis of Certain Manuscripts of F. A. Tsander Dedicated to the Problem of Utilization of the Air in Rocket and Space Technology," Trudy Tret'ikh Chteniy F. A. Tsandera [Works of the Third F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow, 1976, pp. 68-73. /190

Certain problems of a historiographic nature are discussed and a historic-scientific analysis of the ideas of F. A. Tsander on the use of the air in the power plants of specific devices are presented.

Klychnikov, Yu. V., "Comparative Analysis of the Works of F. A. Tsander in the Initial Stage of Development of Rocket-Space Technology," Iz Istorii Aviatsii i Kosmonavtiki, No. 25, Moscow, 1975, pp. 62-72.

A comparative description is presented of the solutions F. A. Tsander developed to the problems of rocket engines, the use of the atmosphere and the problem of the use of "spent" rocket elements with the solutions of similar problems by other pioneers of rocket technology and astronautics. Statements of a priority nature are set forth and proven.

Komarov, V. M., Tarasenko, I. I., "The Working Journal of F. A. Tsander as a Historical Source," Trudy Vtorykh Chteniy F. A. Tsandera [Works of the Second F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow, 1974, pp. 88-97.

A textologic and content analysis of the working journal of F. A. Tsander is presented. A number of new statements are set forth concerning various aspects of the life and creative activity of the scientist.

Korneyev, L. K., "The Life, Creativity and Activity of F. A. Tsander," F. A. Tsander. Problema Poleta pri Pomoshchi Reaktivnykh Apparatov. Mezhplanetnyye Polety [F. A. Tsander, The Problem of Flight by Means of Reaction Apparatus, Interplanetary Flights], Moscow, 1961, pp. 5-73. Separate edition, L. K. Korneyev, Entuziast Mezhplanetnykh Poletov F. A. Tsander [F. A. Tsander, An Interplanetary Flight Enthusiast], Moscow, 1961.

Materials are presented describing the activity of F. A. Tsander in practically all stages of his life. New data are presented on the development by F. A. Tsander of various versions of high thrust LRE and particularly promising systems.

Kurpatenkov, V. D., Krikun, V. V., "The Ideas of Tsander on the Application of Metals as Additives to Liquid Fuels," Trudy Tret'ikh Chteniy F. A. Tsandera [Works of the Third F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," pp. 51-59.

A study is made of various aspects of the ideas of F. A. Tsander on the use of metallic rocket fuel and modern experimental-theoretical investigations developing this type of fuel are described.

Malkin, V. B., "F. A. Tsander and Modern Bioastronautics," Trudy Tret'ikh Chteniy F. A. Tsandera [Works of the Third F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow, 1975, pp. 4-10.

The basic ideas and suggestions of F. A. Tsander concerning the complex of problems of biological support of space flight are described and the current state of individual trends in bioastronautics is discussed.

Mel'kumov, T. M., "The Basic Ideas of F. A. Tsander in the Area of Rocket Engines," Trudy Pervykh Chteniy F. A. Tsandera [Works of the First F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow-Riga, 1972, pp. 7-14.

Most of the original ideas of F. A. Tsander are described. The independence of the research approach of the scientist to the solution of the basic problems of long-range space flight and significance of the contribution of F. A. Tsander to the creation of the principles of rocket-space science and technology are particularly emphasized.

Melovidov, B. I., "The Ideas of F. A. Tsander on the Use of Aerodynamic Forces in Rocket Flight in the Atmosphere," Trudy Pervykh Chteniy F. A. Tsandera [Works of the First F. A. Tsander Readings], Section on "Study of the Scientific Creativity of F. A. Tsander," Moscow-Riga, 1972, pp. 57-64.

A discussion is presented of the priority-value aspect of the activity of F. A. Tsander in the area of the scientific and practical development of ideas for

the use of aerodynamic forces during the flights of rockets in the atmosphere.

Milovidov, B. I., "Some Problems of the Optimization of Rocket Aeroplanes in the Works of F. A. Tsander," Trudy Vtorykh Chteniy F. A. Tsandera [Works of the Second F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow, 1974, pp. 105-108.

A study is made of the works of F. A. Tsander on determination of the mean trajectory values of efficiency of a rocket and an attempt is made to demonstrate the importance of determination of this parameter in modern calculations in which, in the opinion of the author, the significance of this parameter is underestimated.

Merkulov, I. A., "Some Problems of Optimization of Space Flight in the Works of F. A. Tsander," Trudy Vtorykh Chteniy F. A. Tsandera [Works of Second F. A. Tsander Readings], Section on "Astrodynamics," Moscow, 1974, pp. 115-120.

A study is made of problems related to the developments of F. A. Tsander on optimization of local orbital maneuvers, design of spacecraft trajectory corrections and the use of gravitational fields of planets "along the way." /191

Morozov, G. I., "The Works of F. A. Tsander in the Area of Creation of Life Support Systems for Space," Trudy Pervykh Chteniy F. A. Tsandera [Works of First F. A. Tsander Readings], Section on "Life Support Systems and Astrobotany," Moscow-Riga, 1972, pp. 82-87.

Information is presented on the studies of F. A. Tsander on life support systems, extracted by the author from a visual examination of the shorthand records.

Morozov, G. I., "Some Information on the Writings of F. A. Tsander on the Problems of Life Support in Space," Trudy Vtorykh Chteniy F. A. Tsandera [Works of the Second F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow, 1974, pp. 98-104.

An attempt is made to provide a comparative analysis of the chronological sequence of the shorthand writings of F. A. Tsander on the problems of life support with known events in his biography and creative activity. The intensity and variety of investigations of the scientist in the area of life support problems are illustrated.

Moshkin, Ye. K., "Engineering Developments of F. A. Tsander in the Area of Rocket Technology," Iz Istorii Raketnoy Tekhniki [From the History of Rocket Technology], Moscow, 1964, pp. 203-221.

The basic stages in the engineering activity of F. A. Tsander in the area of rocket technology are demonstrated; the works of the scientist on the creation of the OR-1, OR-2 and 10 engines and the initial versions of the GIRD-X rocket are analyzed. Using specific examples of the development of individual technical systems by F. A. Tsander, the characteristic features of his engineering method are noted.

Moshkin, Ye. K., "The OR-2 Engine of F. A. Tsander -- the First Domestic LRE for Manned Reaction Flight Vehicles," Trudy Pervykh Chteniy F. A. Tsandera [Works of the First F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow-Riga, 1972, pp. 25-31.

Some peculiarities of the engineering activity of F. A. Tsander are noted. The basic stages in the development and experimental study of the OR-2 engine are described. The idea of the promise of the individual basic design decisions reflected in the OR-2 project is demonstrated.

Petrov, S., "The Rocket Engines of F. A. Tsander," Aviatsiya i Kosmonavtika, October 1964, Extra Edition, pp. 72-77.

A study is made of the design peculiarities of objects developed at GIRD under the leadership and with the direct participation of F. A. Tsander. The thesis is set forth of the leading role of F. A. Tsander in the formation of a definite trend in domestic rocket construction.

Petrovich, V. G., Ivanov, N. V., "Illumination of the Creative Path of F. A. Tsander," Trudy Pervykh Chteniy F. A. Tsandera [Works of the First F. A. Tsander Readings], Section on "Study of the Scientific Creativity of F. A. Tsander," Moscow-Riga, 1972, pp. 48-56.

The contribution of F. A. Tsander to the early stage of domestic rocket building (1924-1933) is noted.

Some statements set forth in a number of research and literary works on the scientist are criticized.

Pobedonostsev, Yu. A., Merkulov, I. A., "The Ideas of F. A. Tsander on Increasing the Work of the Cycle of a Reaction Engine by Means of a Reverse Cone," Trudy Vtorykh Chteniy F. A. Tsandera [Works of the Second F. A. Tsander Readings], Section on "Investigation of

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Scientific Creativity of F. A. Tsander," Moscow, 1974, pp. 46-53.

A study is made of the reality and effectiveness of the suggestion of F. A. Tsander for increasing the ideal thermodynamic cycle of a rocket engine by supersaturation of the combustion products in a device amounting to a structural continuation of the engine nozzle.

Polyarnyy, A. I., "Some Aspects of the Activity of F. A. Tsander," Trudy Vtorykh Chteniy F. A. Tsandera [Works of the Second F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow, 1974, pp. 54-60.

Based on personal recollections, the author discusses certain aspects of the biography of F. A. Tsander, presenting an evaluation of individual ideas and suggestions of the scientist, and noting the most probable means for their future realization.

Samokhvalova, L. G., "The F. A. Tsander Collection in the Archives of the Academy of Sciences USSR," Trudy Pervykh Chteniy F. A. Tsandera [Works of the First F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow-Riga, 1972, pp. 107-114.

An improved systematization of the materials of the F. A. Tsander collection is presented and individual stages in its creation discussed.

Stradyn', Ya. P., "The Riga Period of the Life and Activity of F. A. Tsander," Trudy Pervykh Chteniy F. A. Tsandera [Works of the First F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow-Riga, 1972, pp. 67-81.

The historical background against which the activity of F. A. Tsander occurred during the Riga period of his life is discussed. Certain social-psychological aspects of the development of the creative individuality of the scientist during the years of his training at Riga Polytechnical Institute are analyzed. /192

Tarasenko, I. N., "Certain Aspects of the Social-Propaganda Activity of F. A. Tsander," Trudy Pervykh Chteniy F. A. Tsandera [Works of First F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow-Riga, 1972, pp. 82-92.

The social-propaganda activity of F. A. Tsander in the area of rocket technology is described. The

position of F. A. Tsander in the work of scientific popularization of the ideas of achievement of interplanetary flights is defined.

Tsander, A. F., "The Slides of F. A. Tsander," Aviatsiya i Kosmonavtika, 1962, No. 10, pp. 18-19.

The illustrative-graphic material which F. A. Tsander used with his many public lectures popularizing the idea of interplanetary flights is presented.

Tsander, A. F., "The Scientific and Technical Heritage of F. A. Tsander," Iz Istorii Raketnoy Tekhnika [From the History of Rocket Technology], Moscow, 1964, pp. 175-202.

A rather detailed review is presented of the works of F. A. Tsander based on materials published up to that time, and new information is presented from the family collection of the scientist. Individual developments of the scientist relating to LRE, jet engines and rocket engines burning metallic fuel are analyzed.

Tsander, A. F., "The Problem of the Works of F. A. Tsander on LRE and Liquid Rockets and His Role in GIRD," Trudy Vtorykh Chteniy F. A. Tsandera [Works of the Second F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow, 1974, pp. 36-45.

In addition to a description of the content of the creativity of F. A. Tsander in the area of rocket technology, the priority-value aspect of his activity is analyzed. Based on archive materials, an attempt is made to clarify certain individual positions reflected in the research literature on F. A. Tsander.

Tsander, A. F., "The Works of F. A. Tsander Concerning the Problem of Flight Trajectories Between Two Planets," Iz Istorii Aviatsii Kosmonavtiki [From the History of Aviation and Cosmonautics], No. 23, Moscow, 1974, pp. 126-144.

A scientific historical analysis is presented of one trend in the studies of F. A. Tsander on astrodynamics, and the specific features of the approaches of various scientists to the solution of similar problems are discussed. In particular the question of planning of trajectories of interplanetary flights in the works of V. Goman is analyzed.

Tsander, A. F., "Some Problems of Optimization of Space Trajectories in the Works of F. A. Tsander," Iz Istorii Aviatsii Kosmonavtiki [From the History of Aviation and Cosmonautics], No. 25, Moscow, 1975, pp. 121-130.

A study is made of the works of F. A. Tsander on the correction of the motion of space vehicles during the final stage of a flight and the investigation of the optimal conditions for imparting additional velocity to the vehicle.

Tsander, A. F., "The Problem of the Investigations of F. A. Tsander in the Area of Space Trajectories and Publication of His Works," Trudy Tret'ikh Chteniy F. A. Tsandera [Works of the Third F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow, 1975, pp. 37-50.

Using the example of the most important works on astrodynamics, various aspects of the creativity of F. A. Tsander are studied concerning the development of the theoretical principles of astronautics. A comparative analysis of the works of F. A. Tsander on the theory of space flight and the corresponding studies of foreign scientists is presented. The thesis of the priority of the scientist in setting forth and analytically developing the idea of the "gravitational maneuver" is presented and proven.

Shtekher, M. S., "The Ideas of F. A. Tsander on the Use of Cryogenic Fuels in Rocket Engines," Trudy Vtorykh Chteniy F. A. Tsandera [Works of the Second F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow, 1974, pp. 28-35.

A discussion is presented of a range of problems characterizing the approach of F. A. Tsander to the problem of rocket fuel and particularly to the problem of the utilization of cryogenic fuel. A number of statements of a priority nature are set forth and demonstrated.

Shtekher, M. S., "F. A. Tsander and the Problem of Rocket Fuels," Trudy Tret'ikh Chteniy F. A. Tsandera [Works of the Third F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow, 1974, pp. 60-67.

A study is made of a variety of investigations of F. A. Tsander on the selection and mastery of various classes of rocket fuels. Statements are formulated and demonstrated reflecting the pioneering nature of the corresponding studies of the scientist.

Shchetinkov, Ye. S., Voronkov, Yu. S., "Fridrikh Arturovich Tsander -- His Role and Significance in the Development of Rocket Building," Iz Istorii Aviatsii i Kosmonavtiki [From the History of Aviation and Cosmonautics], No. 17-18, Moscow, 1972, pp. 219-224.

A study is made of the most important ideas and suggestions of F. A. Tsander, specific trends in his creative activity are studied and a number of statements are made characterizing the priority-value aspect of the creativity of the scientist. /193

Shchetinkov, Ye. S., Belov, B. L., "F. A. Tsander and Contemporary Astronautics," Trudy Vtorykh Chteniy F. A. Tsandera [Works of the Second F. A. Tsander Readings], Section on "Study of the Scientific Creativity of F. A. Tsander," Moscow, 1974, pp. 14-27.

A description is presented of the current state of the most fruitful ideas and suggestions set forth earlier by F. A. Tsander. It is shown that the realization of these ideas and suggestions in their fullest volume and in somewhat modified form is related to the performance of the space programs of the near future.

Yarantsev, O. A., Derunova, E. B., "Development of the Ideas of F. A. Tsander on the Application of Economic Analysis to the Planning of Rocket-Space Technology," Trudy Pervykh Chteniy F. A. Tsandera [Works of the First F. A. Tsander Readings], Section on "Investigation of the Scientific Creativity of F. A. Tsander," Moscow-Riga, 1972, pp. 115-122.

Using specific examples of the scientific-practical activity of the scientist, the approach of F. A. Tsander to the solution of the basic problems of astronautics as an important social-economic problem is illustrated. A general description of the problems and capabilities of economic analysis for the planning of complex rocket-space systems is presented.

BASIC MATERIALS ON THE STUDIES OF F. A. TSANDER IN THE AREA OF ROCKET-SPACE SCIENCE AND TECHNOLOGY FOUND IN THE ARCHIVES OF THE ACADEMY OF SCIENCES USSR[1]

Works of F. A. Tsander

1. a) Die Weltschiffe (Atherschiffe), die den Verkehr Zwischen den Sternen ermoglichen sollen. Die Bewegung in Weltenraum [Spaceships (Ether Ships) Allowing Travel Between the Stars. Movement in Space], 18 September 1908-18 September 1912. Working notebook. Autograph. German language, some in shorthand.
   b) Journal: Entries of observations of weather, types of activity -- study of the literature on spaceships, calculations and design of spacecraft. 18 September 1908-1910. Autograph. Shorthand. List 1, No. 194, 89 sheets.

2. (Air Flight and Space Flight), 11 June 1912-1913. Working Notebook. Autograph. Shorthand. Deciphered notebook appended. Typewritten. German. Manuscript, second copy. Russian. List 1, No. 203, 168 sheets.

3. Various from the area of air flight. Air flight and space flight. The design of high altitude, sealed aircraft. 22 October 1913-21 May 1919. Working notebook. Autograph. Shorthand. German. Interpretations appended: German -- one copy, Russian -- three copies. List 1, No. 204, 169 sheets.

4. Development of problems of astrobotany and human life under spacecraft conditions, 1916-1930. Working notebook. Autograph. Shorthand. Brief interpretation appended. Russian. List 1, No. 213, 183 sheets.

5. Sketches, diagrams, graphs, tables and calculations of investigations of the possibility of combination of a rocket with a mirror. 3 August 1921-18 July 1923. Working notebook. Autograph. Shorthand. German. Interpretation of text appended. Russian and German. List 1, No. 238, 139 sheets.

6. Sketches, calculations of beams, tension members, LRE chambers related to plan of space aeroplane of F. A.

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[1] In preparing this appendix, it was considered expedient to organize the materials within the framework of the following thematic sections: "Works of F. A. Tsander" and "Materials on the Activity of F. A. Tsander".

Tsander. 24 January-30 June 1922. Working notebook. Autograph. Shorthand. German. List 1, No. 243,

7. Interplanetary voyage. 4 July 1922-3 December 1928. Working notebook. Autograph. Shorthand. German. 11 notebooks of interpretation of text appended. German and Russian. List 1, No. 245, 605 sheets. /194

8. "Flights to Other Planets," 6 December 1923, Articles and conspectus. Autograph. Authorized typescript. Pages from the journal "Tekhnika i Zhizn'", No. 3, 1924 with publication of the article attached.

9. "Flights to Other Planets" (1923). Article. Autograph. List 1, No. 1, 34 sheets.

10. "Thermal Design of a Rocket," 12-17 January 1924, Article two versions. Initial version has title "Design of Rocket for Interplanetary Spaceship". Autograph. Authorized typescript. File 1, No. 39, 47 sheets.

11. "Calculation of Flight of Interplanetary Ship in the Atmosphere. Ascent," 14 (January) 1924. Article. Autograph. Typescript. List 1, No. 14, 16 sheets.

12. "Calculation of Flight of Interplanetary Spaceship in the Atmosphere. Gliding Descent from Interplanetary Space to Surface of Earth," 30 January 1924-28 October 1927. Article. Autograph. Authorized typescript. Typescript. Fragments of calculations of gliding descent with comments of Professor V. P. Vetchinkin of 8/02/1927 appended. List 1, NO. 12, 111 sheets.

13. "List of Problems Arising in Connection with Flights to Other Planets Which Need Solution," 15 February 1924. Autograph. List 1, No. 24, 1 sheet.

14. "Numerical Example of Gliding Descent from Interplanetary Space to the Earth," 18 February-4 March 1924. Article. Autograph. Typescript. List 1, No. 30 sheets.

15. "Determination of Mutual Position of Planets During Departure and Arrival," 1924 article. Incomplete utograph. List 1, No. 8, 3 sheets.

16. "Correction of Flight Upon Approach to Planets in Order to Achieve Safe Descent to Desired Location and Change Flight Path by the Action of the Planets," 6 March-1 April 1924. Article. Autograph. List 1, No. 1a, 8 sheets.

17. "Flights to Other Worlds," 11 August 1924. Article. Autograph. List 1, No. 2, 3 sheets.

18. "Design of Rockets Emitting Both Volatile and Solid Products of Combustion or Materials from Their Nozzles," 27 September 1924. Article (beginning). Autograph. Copy. List 1, No. 79, 2 sheets.

19. "Description of the Interplanetary Spaceship of F. A. Tsander," 1924. Theses and drawings. Autograph. Authorized typescript. Typescript. Tracings and blueprints. List 1, No. 31, 66 sheets.

20. "Approximate Determination of the Change in Cost of Interplanetary Flights Due to Variation in the Quantity of Solid Combustion Products," Article (not completed), 28-39 January 1925. Autograph. List 1, No. 40, 6 sheets.

21. "The Use of Thin Sheets," 1924-30 December 1925. Fragment of article. (Reference data on preparation of thin nickel plates). Autograph. List 1, No. 9, 3 sheets.

22. "The Flight of Long-Range Rockets Outside the Atmosphere," 12 January 1925-12 December 1929. Article. Initial name of article "Calculation of Flight of Long-Range Rockets Outside the Atmosphere." Autograph. Authorized typescript. Retyped edited version for publication appended. List 1, No. 6, 37 sheets.

23. "Calculations for the Aviation and Interplanetary Engine of Engineer F. Tsander," 11 April 1925. Three articles. Autograph. List 1, No. 33, 5 sheets.

24. "Deflection of Meteoroids and Reduction of Their Influence by the Electrostatic Electricity Emitted by an Interplanetary Spaceship," 26 June-9 July 1925. Article. Autograph. List 1, No. 20, 3 sheets.

25. "Flights to Other Planets and the Moon," 28-15 August 1925. Materials for book: chapter titles, foreword, detailed conspectus. Autograph. List 1, No. 3, 6 sheets.

26. "Flights to Other Planets. Theory of Interplanetary Voyages. (Determination of Flight Paths, Necessary Additional Velocities and Time Required for Flights)," 14 September 1925-12 March 1929. Article. Two versions. Initial version contains additional section, "Determination of Paths for Flights in Space with /195

Return to Earth after a Whole Number of Years." Autograph. Typescript with author's corrections. List 1, No. 3, 43 sheets.

27. "Flight to Other Planets by Means of a Sphere Made of Thin Sheets," 6 December 1925. Article (Incomplete). Autograph. Typescript. List 1, No. 10. 5 sheets.

28. "The Suitability of Acceleration of the Flight of an Interplanetary Ship by the Action of a Rocket at Moments When its Flight Velocity is High," 9 December 1925-14 May 1929. Article. Autograph. Typescript. List 1, No. 5, 10 sheets.

29. "A Rocket Engine Operating with Metallic or Generally Solid Fuel," 1925-1928. Article. Typescript with corrections by Professor M. K. Tikhonravov. List 1, No. 81, 41 sheets.

30. "Interplanetary Voyages," (Study of the possibility of the combination of a rocket with a mirror), 28 January 1926-26 August 1928. Working notebook. Autograph. Shorthand. German. List 1, No. 260a, 144 sheets.

31. "Design of Hydrogen-Oxygen Rockets," 15 March 1926. Article (incomplete). Autograph. Copy. List 1, No. 41, 2 sheets.

32. "Flights to Other Planets. The First Step into Limitless Space. (Theory of Interplanetary Voyages)," 17 October 1926. Chapter headings for book. Autograph. Authorized typescript. List 1, No. 3a, 39 sheets.

33. Sketches of general views, parts of the OR-1 engine and liquid fueled rocket. 14 March 1928-19 July 1929. Autograph. List 1, No. 21, 5 sheets.

34. "The Design of High Altitude Rockets Intended for Investigation of the Upper Layers of the Atmosphere," 27 March-24 May 1928. Article (incomplete). Autograph. Typescript. List 1, No. 17, 7 sheets.

35. "Calculation of the Transmission of Heat Through Sections of Pipe Through Which a Gas Moves with Constant and Variable Wall Temperature and Determination of the Pressure Drop Due to Friction of the Gas Against the Wall, Number of Pipes and Efficiency of Combustion Chamber," 8 August 1928. Article (beginning). Autograph copy. List 1, No. 43, 2 sheets.

36. "List of Alloys of Metals Which Could be Used as Rocket Fuels," 16 September 1928. Autograph. Copy. List 1, No. 82, 2 sheets.

37. "Preparation of Magnesium Alloys for Casting. Comparison of Information Given by Various Authors," 28 September 1928. Autograph. Copy. List 1, No. 83, 1 sheet.

38. Combustion of metals. 27 October-27 December 1928. Description of experiments. Typescript. German. List 1, No. 84, 66 sheets.

39. "Calculation of the Experimental OR-1 Rocket Engine," 30 September 1929-2 April 1931. Article. Autograph. List 1, No. 44, 95 sheets.

40. "The Straightening Force of a Rubber Sleeve Supplying Air Under Pressure to the R-1 Reaction Engine," 26 December 1929. Autograph. List 1, No. 56, 4 sheets.

41. List of materials relating to planning of OR-1. 1929-1931. Manuscript. Typescript. List 1, No. 67, 4 sheets.

42. "Determination of Weights of Parts of Experimental OR-1 Device," 11-17 May 1930. Design and cost calculation. Autograph. List 1, No. 57, 4 sheets.

43. "Approximate Determination of Cost of Experimental Reaction Devices Intended for Construction," 10-21 June 1930. Autograph. Copy. List 1, No. 51, 5 sheets.

44. "Various Calculations for the Experimental OR-1 Device," 16 September 1930-15 May 1932. Article. Autograph. List 1, No. 59, 22 sheets.

45. "Calculations of Reverse Cone of Rocket Serving to Increase Exhaust Velocity," 25 December 1930. Autograph. Copy. /196
List 1, No. 45, 1 sheet.

46. "Assignment for Planning of a Jet Pump," 18 January 1931. Autograph. Typescript. List 1, No. 61, 5 sheets.

47. "Design of a Jet Pump. Calculation of Normal and Reverse Cone and Nozzle of Exp(erimental) OR-1 Device," 28 January 1921. Autograph. List 1, No. 62, 1 sheet.

48. "The Problem of Flight by Means of Reaction Apparatus," 5 April 1931. Materials for book: a) Foreword (incomplete); introduction, beginning of chapter 1; b) Insert for page 12: "Calculation of Jet Pumps,"); c) Portion of headings for chapter 16. Autograph. Typescript. List 1, No. 7b, 12 sheets.

49. General plan for design of reaction engine operating on liquid fuel and liquid oxygen intended for installation on aeroplane. 13 September-28 October 1931. Autograph. Authorized typescript. List 1, No. 68, 5 sheets.

50. "Reaction Engines and Supplements for Ordinary Internal Combustion Engines and Replacements for Them," 20 September 1931. Conspectus of article. Authorized typescript. Typescript. List 1, No. 92, 2 sheets.

51. "Reaction Engines and Their Combination with Ordinary Internal Combustion Engines," 26 September 31. Article. Authorized typescript. List with editing marks by the journal "Samolet" for publication or article appended. Published in journal "Samolet", No. 1, 1932. List 1, No. 96, 8 sheets.

52. "Design of Nozzle No. 7 Consisting of Forward and Reverse Cone," 1 November 1931. Article. Authorized typescript. List 1, No. 46, 15 sheets.

53. "Temperature, Pressure, Specific Gravity, Velocity of Gases and Corresponding Diameter of Cross Section and Distance of Cross Section from Apex of Cone at Various Points on Forward Cone," 22 December 1931. Fragment of article. Authorized typescript. List 1, No. 2.

54. "Reaction Engines Operating with Materials Yielding Not Only Volatile, But Also Solid Combustion Products," 17 May 1932. Article (incomplete). Authorized typescript. List 1, No. 85, 16 sheets.

55. Design elements of LRE. 23 November 32-13 February 1933. Working notebook. Autograph. Shorthand. List 1, No. 283, 26 sheets.

56. "Design of Reaction Engines and Their Combination with Engines of Other Types. Reaction Engines for Which Oxygen Necessary for Combustion is Taken On-Board the Aircraft, 8 December 1932." List of materials. Developed plan, chapter headings and portion of book. Autograph. Authorized typescript. List 1, No. 98, 19 sheets.

57. Description of OR-2. 4 January-9 February 1933. Autograph. Shorthand. List 1, No. 285, 10 sheets.

58. "The Stratosphere," 12 February 1933. Article. Supplement. Authorized typescript. Lists of editors comments of "Tekhnicheskaya Entsiklopediya" for additions appended. List 1, No. 17a, 12 sheets.

59. "Calculation of the Liftoff of a Rocket," 19 February 1933. Article. Autograph. Rough version. List 1, No. 18, 3 sheets.

60. "The Best Speed of a Rocket at Speeds Less than the Speed of Sound and for the Lower Layers of the Atmosphere," 25 February 1933. Article (incomplete). Autograph. Rough draft. List 1, No. 19, 3 sheets.

61. "The Use of Materials Yielding Solid Combustion Products as Fuels for Rockets," b/d. Article (beginning). Autograph. List 1, No. 86, 1 sheet.

62. Album of photographs of parts and OR-1 and OR-2 engine. b/d. (37 prints). List 1, No. 66, 12 sheets.

63. "Oxygen-Gasoline Rocket for High Altitude Flights." b/d. Drawings. Autograph. List 1, No. 21a, 3 sheets.

64. "System for Fuel Feed to LRE Chamber. Three-Dimensional Drawing," b/d. Drawing. List 1, No. 78, 1 sheet.

Materials on the Activity of F. A. Tsander /197

Lectures and Reports

1. "Report of Engineer F. A. Tsander on His Invention: an Aeroplane for Flight on the Earth's Atmosphere to Other Planets and the Significance of the Development of Aviation in This Direction," Report at Plantwide Meeting of State Aviation Plant No. 4 (Formerly "Motor" Plant), April 1923. Autograph. Machine copy. List 1, No. 25, 9 sheets.

2. "Report of Engineer F. A. Tsander on His Invention: an Aeroplane for Flight on the Earth's Atmosphere to Other Planets and the Significance of the Development of Aviation in This Direction," Conspectus for report and report at Scientific-Technical Committee of VSNKh, May 1923. Autograph. Machine copy. List 1, No. 26, 11 sheets.

3. Materials of F. A. Tsander on report made by him at theoretical section of Moscow Society of Astronomy Enthusiasts, 20 January 1924. ("Conspectus..." and "Resume..."). Autograph. Authorized typescript. List 1, No. 27, 4 sheets.

4. "Report at Scientific-Popular Section of the Society for Research on Interplanetary Voyages Concerning a Reaction Engine," Read 31 July 1924. Autograph. Copy. List 1, No. 39a, 1 sheet.

5. Materials for report "On Flights to Other Planets," delivered 17 November 1924 in Leningrad, September 1924. Autograph. List 1, No. 2a, 2b, 3b, 4 sheets.

6. "Conspectus for Report of Engineer F. A. Tsander on His Interplanetary Spaceship." Reports of 1, 4, 5 October 1924 made at debate at Physics Institute of First Moscow University. Poster of debate and rough draft version of conspectus with sketches appended. Autograph, machine copy. Poster -- original and machine copy. List 1, No. 29, 11 sheets.

7. "Report of Engineer F. A. Tsander on Interplanetary Voyages," (1924). Autograph. List 1, No. 7v, 6 sheets.

8. Copy of slides of Tsander of blueprints (1924-1925). List 1, No. 4/23a, 23b, 53 sheets.

9. Lists of slides of F. A. Tsander, 30/06/25 - 22/12/25. Autograph. List 1, No. 7d, Sheet 4; No. 6v, Sheet 1; No. 32, 1 sheet.

10. "Flights to Other Planets and the Moon," Astronomical portion of lecture and list of slides for lecture. 30 June-27 October 1925. Autograph. List 1, No. 3g, 4 sheets.

11. "Report on My New Works in the Area of Interplanetary Voyages," 15 November 1925. Autograph, typescript. List 1, No. 4a, 4 sheets.

12. "Lecture on Interplanetary Voyages...," 15 September 1927. Autograph. List 1, No. 4b, 1 sheet.

13. Announcement of reading of reports "Possibility of Reaching High Altitudes Using the Principles of Astronautics," (15 March 1928) and "Preliminary Work on the Construction of a Reaction Apparatus," 30 November 1928, read by Tsander at sessions of Commission for Scientific Air Flight of Moscow Aerological Observatory. 10 March-30 November 1918. Agendas, autograph. List 3, No. 47, 5 sheets.

14. "The Problem of Flight by Means of Reaction Devices and Problems of Superaviation," with supplement "Immediate Problems on Preparation for Interplanetary Voyages." Report for presentation at Fifth International Congress on Air Navigation in the Hague, 1-6 September 1930, 25/03/1930-30/03/1931. Authorized typescript with corrections by F. A. Tsander. List 1, No. 7a, 98 sheets.

15. List of illustrations for report of Tsander at Technical Conference on Reaction Engines at IAM, 25/03/31. Autograph. List 1, No. 7d, 3 sheets.

16. The current state of the problem of application of reaction engines and reaction aircraft abroad and here in the USSR. Developed plan and theses of report for conference of representatives of USSR Civil Aviation, 20/01/1932, 2/12/1931. Authorized typescript. Machine copy. List 1, No. 93, 13 sheets.

17. Report to Section on Inventions of State Economic Conference and Administration of Association of Inventors concerning the high-pressure engine and plan for an interplanetary spacecraft and certificate of AIZ with request for all institutions to support and cooperate with the work of engineer Tsander. 20/05-15/07/22. Autograph. Original. List 3, No. 3, 3 sheets. /198

18. "Proposed Work of Scientific Research Section of Society for Study of Interplanetary Voyages," Organizational Report, read 15/07/24. Autograph. Machine copy. List 1, No. 1b, 3 sheets.

19. "Works Suggested for Performance by ODVF Cell at State Aviation Plant imeni M. V. Frunze in the Area of Aviation and High Altitude Rockets in Order to Aid Cultural and Military Affairs and Prepare for Interplanetary Voyages," Brief Abstract. 27/04/25. Autograph. List 1, No. 6a, 1 sheet.

20. "Description of Work and Designs Performed in Connection with the Invention: 1) Of a High-Pressure Engine Operating Like a Diesel Burning Petroleum or Fuel Oil and Liquid Oxygen and 2) Of a Rocket Operating with Any Fuel, Liquid Oxygen and Any Melted Metal," 10/07-16/07/25. Application for invention. List 1, No. 33a, 4 sheets.

21. "Calendar Plan for Work of Interplanetary Subsection of Sport-Aviation Section of Mosaviakhim for January-April 1926," 24/01/26. Autograph. List 3, No. 44, 1 sheet.

22. Application to Scientific and Technical Committee of VSNKh for funds for continuation of scientific and technical work in the area of interplanetary voyages. 8 October 1926. Autograph. List 2, No. 101, 2 sheets.

23. Report of V. P. Vetchinkin of 13 February 1927. Authorized typescript with note on reverse. List 4, No. 4, 2 sheets.

24. Application to Scientific Department of Glavnauka requesting to be allowed to work in the area of interplanetary voyages at TSAGI or Aviation Trust and preparation for press of book "On Interplanetary Voyages," and report of results of analysis of his presentation. 8/10/26, 7/03-14/09/27. Autograph. Authorized typescript (two copies). List 3, No. 11, 11 sheets.

25. Note of K. E. Voroshilov with request to work at TSAGI or at Plant for Special Engine for High Altitude, High Speed Aircraft and Long-Range Rockets. 9/06/27. Autograph. Copy. List 3, No. 8, 2 sheets.

26. "List of Works to be Performed by Engineer F. A. Tsander in the Area Concerning Simultaneously both Military Affairs and Interplanetary Voyages and Directed Toward Reinforcement of Red Airforce," Prospective plan. 30/06/27. Autograph. Two copies. Machine copy. List 1, No. 48, 9 sheets.

27. Application to Chairman of the Board of TSAGI, Professor S. A. Chaplygin, requesting to be allowed to work on rocket themes at TSAGI. 10/09/27. Autograph. Three copies. List 3, No. 9, 1 sheet.

28. Application to People's Commissar for Education, A. V. Lunacharskiy. 14 September 1927. Autograph. Rough Draft. List 4, No. 2a, 1 sheet.

29. Developed plan for small volume of work on reaction engines (OR-1 and OR-2) made up for presentation to technical conference of 23/02/1930, 27/02/1930. Autograph. Copy. Machine copy. List 1, No. 49, 5 sheets.

30. "Program of Large Volume Work on Reaction Engines and Preparation for So-Called Superaviation," 30/04-3/05/30. Autograph. Two copies. Machine copy. List 1, No. 50, 20 sheets.

31. Composition and plan of operations of Bureau for the Study of Reaction Motion (BIRD), 18/07/31. Authorized typescript. List 3, No. 82.

32. Brief plan for theoretical and practical work on rocket-space themes, 20/07/31. Typescript with author's corrections. List 1, No. 52a, 4 sheets. /199

33. "Types of Reaction Engines Suggested for Installation on the First Rocket Plane in Honor of the '15th Anniversary of October,'" Authorized typescript. 10/09/31. List 1, No. 90, 2 sheets.

34. Announcement of formation in CC Osoaviakhim of Group for the Study of Reaction Engines (GIRD) and announcement of search for those desiring to work on planning and construction of reaction engines. 23/09/31. Autograph. Authorized typescript. List 3, No. 23, 4 sheets.

35. "Program of Operations on Reaction Engines at First Laboratory of IAM BR "R" for 1932. 1/02/32. Authorized typescript. List 1, No. 95, 10 sheets.

36. "Program of Operations of Group of Engineer F. A. Tsander for 1932," List of numbers of group appended. 21/05/32. Authorized typescript. List 3, No. 30, 4 sheets.

37. "The Work of Team No. 1 of GIRD Between 20 September and 25 October 1932," Report and conspectus. 26/09-26/10/32. Autograph. Authorized typescript. List 3, No. 27, 7 sheets.

38. List of equipment and fuel for team No. 1 of GIRD. 4 November 1932. Autograph. Typescript with author's dating. List 3, No. 33, 2 sheets.

39. "The OR-O Installation," Report to Chief of GIRD. 22/11/32. Autograph. Typescript. List 1, No. 53, 3 sheets.

40. Report on work performed by first GIRD team in January 1932 on ORD-2 and objects 10 and 13. 4/01/33. Autograph. Draft. List 3, No. 32, 1 sheet.

41. "A List of Objects Suggested for Development in 1933 by Team No. 1 of GIRD in the Section for Cooperation with the Aviation Industry of CC Osoaviakhim," Machine copy. b/d. List 3, No. 34, 3 sheets.

Publication Activity

42. Manuscript for publication of Tsander's article "Flight of Long Distance Rockets Outside the Atmosphere," in 'Tekhnika Vosdushnogo Flota," 3/12/29-3/3/30, from List 1, File 6, 21 sheets.

43. Accompanying letter to editors of "Aviapromyshlennost'" for article "Problem of Flight by Means of Reaction Apparatus and the Problem of Superaviation in General," 20 July 1930. Authorized typescript. Machine copy. List 3, No. 60, 2 sheets.

44. Materials for translation and publication in Russian of the book of Professor G. Oberth "Paths to Space Flight," 1930-March 1934. Autograph. Authorized typescript. List 3, No. 61, 54 sheets.

45. Publication agreement and correspondence with publishers concerning publication of works of F. A. Tsander "Calculation of Reaction Engines and Their Combination with Engines of Other Types" and "The Problem of Flight by Means of Reaction Apparatus." Originals. Authorized typescript. Copies. 19 February 1931-9 February 1933. List 3, No. 65, 27 sheets.

46. Materials for publication of works of K. E. Tsiolkovskiy (Plan of Jubilee Collection, comments of editor F. A. Tsander, correspondence with publishing house, translation of articles of K. E. Tsiolkovskiy into German, etc.), 27 June-11 December 1932. Authorized typescript. Originals. List 3, No. 64, 53 sheets.

Pedagogic Activity

47. On interplanetary voyages. Conspectus for lectures to be read at Academy of the Airforce imeni N. Ye. Zhukovskiy during second semester of 1924/1925 and 1926/1927 academic years. 14/12/24-30/04/27. Autograph. Authorized typescript. Machine copy. List 1, No. 2v, 17 sheets.

48. Materials related to the activity of Tsander at the Higher Aeromechanical School. 13/05-13/08/1930. List 3, No. 52, 13 sheets.

49. Materials related to the activity of Tsander at Moscow Aviation Institute: program of work, assignments, materials for lectures, for textbook, etc. 25/10/1930-20/06/1931. List 1, No. 7g, No. 44a; List 3, No. 54, No. 55, 22 sheets.

ABSTRACTS OF ARTICLES IN THIS COLLECTION

SOME ASPECTS OF THE STUDY OF THE SCIENTIFIC HERITAGE OF F. A. TSANDER, Yu. S. Voronkov, p. 1 /202

An attempt is made to analyze the possible methodological approaches for development of the scientific heritage of F. A. Tsander. The possibilities and limitations of each approach are shown. Based on analysis of specific factual material, it is demonstrated that it is necessary in evaluating the contributions of F. A. Tsander to the development of rocket and space technology to consider as much as possible the actual creative personality of the scientist. This approach, the author believes, allows the specific purpose of the development of the scientific heritage to be achieved -- recreation of the single historic process, harmonically including both scientific achievements and the complex process of their production.

THE RIGA PERIOD IN THE LIFE AND ACTIVITY OF F. A. TSANDER (1887-1915), Ya. P. Stradyn', p. 8

This work shows the historical background against which the activity of F. A. Tsander occurred during the Riga period of his life. Certain aspects of the biography of F. A. Tsander in this period are discussed. Certain social and psycological aspects of the formation of the creative individuality of the scientist during the years of his study at Riga Polytechnical Institute are analyzed.

THE BASIC IDEAS OF F. A. TSANDER IN THE AREA OF ROCKET MOTORS, T. M. Mel'kumov, p. 20

This work describes most of the original ideas of F. A. Tsander. The independence of the investigative approach of the scientist to the solution of the basic problems of future space flight is emphasized and the significance of F. A. Tsander's contribution to the creation of the principles of rocket-space science and technology is noted.

THE IDEAS OF F. A. TSANDER ON INCREASING THE WORKING CYCLE OF A REACTION ENGINE BY MEANS OF AN INVERTED CONE, Yu. A. Pobedonostsev and I. A. Merkulov, p. 27

Thermodynamic studies of the increase in the area of the Rankin cycle by redistribution of gas in the nozzle with subsequent cooling and compression are performed. The area of the parameters of the cycle in which this increase in area of

the cycle yields a significant increase in the exhaust velocity of the gas from the nozzle of the rocket engine is determined.

THE STRUCTURAL PECULIARITIES OF THE PLAN FOR THE INTERPLANETARY AEROPLANE-SPACECRAFT OF F. A. TSANDER, Yu. V. Biryukov, p. 34

The basic stages in the work of F. A. Tsander on the creation of the plan for the "interplanetary spaceship-aeroplane" (ISA) are discussed. Various aspects of the creativity of the scientist related to the development of the plan for the ISA and the general solution of the problem of the supply of energy to a manned space flight are analyzed. The thesis of the fruitfulness and promise of the individual ideas technically embodied in the ISA plan is defended.

THE IDEAS OF F. A. TSANDER FOR THE USE OF AERODYNAMIC FORCES IN THE FLIGHT OF ROCKETS IN THE ATMOSPHERE, I. A. Merkulov, p. 47

In the scientific creativity of F. A. Tsander, a central position is occupied by the development of the idea of the winged interplanetary spacecraft. The scientist has priority in a number of areas of the development of this problem. He set forth and developed the following suggestions: 1) creation of air-space vehicles and their utilization for intercontinental flights; 2) creation of a winged spacecraft with variable wing area; 3) utilization of wings retracting into the body as fuel; 4) creation of a single design for a winged spacecraft with a combined power plant. F. A. Tsander developed a plan for a winged two-stage spacecraft which utilized his suggestions.

THE PROBLEMS OF ROCKET DYNAMICS IN THE CREATIVITY OF F. A. TSANDER, B. L. Belov, p. 54

The complex of historic-scientific problems characterizing the creativity of Tsander in the development of problems of flight dynamics of long-range ballistic rockets is analyzed for the first time. This work analyzes the content of the corresponding developments of the scientist, presenting comparative characteristics of the studies of Tsander and the works of his contemporary foreign pioneers of rocket technology (G. Oberth, Esnault-Pelterie) and discusses certain problems of the genesis of rocket dynamics as an independent scientific and technical discipline.

THE PROBLEMS OF THE INVESTIGATIONS OF F. A. TSANDER IN THE AREA OF SPACE TRAJECTORIES AND PUBLICATION OF HIS WORKS, A. F. Tsander, p. 66

This work shows that a number of the primary statements of astrodynamics related to individual space trajectories, space maneuvers, were set forth and scientifically developed by F. A. Tsander when such statements had never yet appeared in the world literature. It is shown that Tsander, earlier than other authors, proved the energetic optimality of tangential ("goman") ellipses in the case of circular coplanar planetary orbits. /203

THE WORKING JOURNAL OF F. A. TSANDER AS A HISTORICAL SOURCE, V. M. Komarov and I. N. Tarasenko, p. 79

This work attempts to analyze the working journal of F. A. Tsander, a pioneer of Soviet rocket technology. This journal is a manuscript which is stored in the Archives of the Academy of Sciences USSR, covering the period from 5 September 1930 through 5 August 1932 and containing information on work in the area of reaction technology performed in the USSR in this period. Using specific examples, the significance of the notebook as a historical source for studies in the area of this history of rocket technology is demonstrated. Earlier unpublished information on the first experimental installation of Tsander, the OR-0, is presented.

SCIENTIFIC AND TECHNICAL ANALYSIS OF THE DECIPHERED MANUSCRIPTS OF F. A. TSANDER, Yu. V. Klychnikov, p. 87

This work analyzes peculiarities of the interpretation of the manuscripts of F. A. Tsander stored in the Archives of the Academy of Sciences USSR and not yet published. Furthermore, all manuscripts of F. A. Tsander are classified, and certain of the manuscripts of Tsander interpreted by the author and dedicated to the problem of aviation and astronautics are analyzed. In particular, the combined rocket-aircraft system, an aircraft with a rocket engine, a rocket with fuel tanks located outside the hull of the rocket and a combined engine installation, air forcing of rocket engines, a plan for an "air-breathing reaction engine and its combination with a gas turbine", etc. are studied.

THE F. A. TSANDER COLLECTION IN THE ARCHIVES OF THE ACADEMY OF SCIENCES USSR, L. G. Samokhvalova, p. 104

This work attempts an archeographic description of the archive collection of the materials of F. A. Tsander. The history of formation of the collection is described. The materials in the collection are classified and each of its five parts is analyzed.

THE THEORY OF OPTIMAL DIRECT FLOW ROCKET ENGINES WITH AIR-CHAMBER AFTERBURNERS, Yu. M. Annushkin, L. N. Druzhinin and V. A. Sosunov, p. 111

The idea of F. A. Tsander on the use of the air to improve the economy of rocket engines is developed. A study is made of the effectiveness of a ramjet engine during the launch ($M < 1.5$-2) and main ($M = 2$-6) sections of the flight of a rocket. Based on schematization of the process in single-nozzle and multiple-nozzle ramjets, a generalized experimental dependence is produced of the completeness of combustion of various fuels on the equivalent length of the air combustion chamber of the ramjet. Analysis using a similar dependence has shown that expedient values of relative fuel consumption, completeness of combustion, effective specific impulse of the engine depend strongly on the equivalent combustion chamber length and flight velocity. An approach is formulated to the combined optimization of flight modes, dimensions (mass) of ramjets and flight conditions.

THE POSSIBILITY OF USING THE CHEMICAL ENERGY OF THE BONDING OF METALS WITH NITROGEN IN THE AIR IN JET ENGINES, V. M. Khaylov, p. 121

A study is made of the possibility of using the thermal effect of interaction of certain metals of groups II and III of the periodic table (Be, B, Al, Mg) with nitrogen in a jet engine. On the example of calculation analysis of the combustion of borohydrides in air with a shortage of oxygen, it is shown that in the case of equilibrium flow of the processes in the combustion chamber and nozzle of the engine, the thermal effect of formation of metal nitrides can be used to increase the thrust of flight vehicles with ramjet engines.

THE POSSIBILITY OF USING THE STRUCTURAL ELEMENTS AS FUEL AND OTHER PECULIARITIES OF HYPERSONIC RAMJET ENGINES, A. T. Berlyand, V. I. Penzin and V. A. Eysmont, p. 130

A study is made of various rules of the change of shape /204
of the flow-carrying portion of a hypersonic ramjet when the material of the walls of the internal tract of the engine is used as a fuel. The possibility is shown of decreasing the losses in thrust of the engine related to variability of the shape of the contour of its flow-carrying portion. The advantages of the use of the materials of the solid walls as fuel in comparison to liquid hydrocarbon fuels are demonstrated.

THE INFLUENCE OF SHIELD PARAMETERS ON ESTIMATION OF THE EFFECTIVENESS OF A SOLAR SAIL, I. A. Merkulov and I. A. Khoromskiy, p. 140

The influence of the parameters of solar screens of both types on the comparative weight estimates of solar sails and ionic engines supplied by solar batteries is studied. The area of these parameters where the solar sail has an advantage over the ion power plant is established. The graphs presented in the work allow the known values of parameters of the solar sail and solar batteries to be used to establish the duration of the functioning of the power plants for which the advantage in the weight respect goes over from the ionic power plant to the solar sail.

THE THEORY OF THE GAS THERMAL COMPRESSOR, R. I. Kurziner, A. N. Knyazev and I. V. Zakharov, p. 147

A theoretical foundation is provided for the possibility of improving the thermodynamic cycle of a reaction engine as a result of deep cooling of the gas stream by evaporation and endothermic interaction of a liquid sprayed into the gas stream. The practical impossibility of increasing the total flow pressure as a result of cooling through the walls of the channel is demonstrated. The results of an experimental study indicate the correctness of the theoretical conclusions.

IGNITION AND COMBUSTION OF METAL PARTICLES, L. A. Klyachko, p. 155

A study is made of the ignition of metal particles with various oxidation rules, the influence on ignition temperature of particle dimensions, pressure and composition of the oxidizing medium, ignition of a gas suspension of metal particles (limits of ignition as to heat liberation and combustion). The time of combustion of particles of low-boiling metals is given. The significance of radiation heat exchange for the propagation of a flame in a gas suspension of particles is demonstrated.

THE USE OF METAL FUEL IN NUCLEAR ON-BOARD POWER PLANTS FOR SPACE, L. A. Kvasnikov, p. 164

In a number of his studies, F. A. Tsander predicts the need to develop on-board power plants for space vehicles and anticipates the use of metal components, particularly alkali metals, as the basic power carriers. Analyzing these suggestions from the modern standpoint, it is not difficult to show their development in modern astronautics. The problem of selection of fuels is particularly acute in the creation of promising power plants based on fuel elements with direct

production of electric power from chemical energy. Metallic fuels based on alkali metals can be used in regenerative fuel elements, in which the volatile component is evaporated due to the heat of a nuclear or solar power supply, providing a continuous cycle of conversion of thermal energy to electric power. This work shows the influence of the basic parameters of the cycle and the mode of the fuel element on the power-weight characteristics of an installation.

THE USE OF TANGENTIAL TRAJECTORIES TO LOWER THE HIGHLY ELLIPTICAL ORBITS OF ARTIFICIAL SATELLITES OF THE PLANETS, P. Ye. El'yasberg and N. A. Eysmont, p. 174

A study is made of problems of the control of motion of an artificial satellite of a planet, transferred by means of aerodynamic braking from a highly elliptical orbit to a low, near circular orbit. An algorithm for control of switching of the engine is developed, providing the minimum time of transfer to the low orbit with a limitation on the maximum equilibrium temperature of the surface of the satellite. Estimates are presented of the time of transition and of the necessary velocity characteristics.

ALGORITHM FOR CORRECTION OF THE PROGRAMMED MOTION OF A VEHICLE WITH A LOW-THRUST ENGINE, M. S. Konstantinov and G. G. Fedotov, p. 184

A method is suggested for reducing the problem of synthesis of the rule of correcting control for a spacecraft with an electric reaction engine to a conditional extremal problem. The correcting control is selected in the form of a piecewise-constant function of the phase coordinates of the vehicle. A study is made of a model problem concerning perturbed motion of a spacecraft in a forceless field.

THE ORIENTATION OF A SOLAR SAIL, V. I. Popov and I. O. Yanov, p. 195 /205

A study is made of passive systems intended for long-term orientation of a solar sail at a given angle to the rays of the sun. The dynamics of the planar vibrating motion of a system are studied considering thermal and elastic deformations of the structure.

ENTRY CORRIDORS INTO THE ATMOSPHERE OF A PLANET FOR THE MANEUVER OF TRANSITION FROM A HYPERBOLIC TRAJECTORY TO A SATELLITE ORBIT AROUND THE PLANET, N. A. Eysmont, p. 204

Problems are solved, related to the selection of optimal control for transfer from a hyperbolic trajectory to an

orbit of a satellite of a planet. It is suggested that the spacecraft initially be braked in the atmosphere of the planet by the influence of aerodynamic forces, then be transferred by the use of its engine to the assigned satellite orbit. The results of calculations of the width of the entry corridor with a limitation on the total necessary rocket dynamic velocity changes are presented, illustrating the effectiveness of optimal control.

ANALYSIS OF TRAJECTORIES AND PARAMETERS OF A VEHICLE WITH LIMITED ENGINE POWER BY THE METHOD OF TRANSPORTING TRAJECTORIES, M. S. Konstantinov, p. 213

This work is dedicated to the development of the method of the transport trajectory. The development is reduced to expansion of the class of transport trajectories as trajectories of active flight with specially selected control rules. The control rule allows analytic investigation of the trajectory of the apparatus. The large number of control constants of the control rule allows good approximation of the transport trajectory to the optimal trajectory, which presumes success in linearization of the equations of motion in the method of transport trajectories.

THE MOVEMENT OF A SATELLITE IN A KNOWN INERTIAL SYSTEM OF COORDINATES, V. P. Semenko, p. 223

This work presents equations for perturbed motion of a satellite in a specially rotating system of coordinates. The system of coordinates is such that the motion of the satellite in this system is central with arbitrary forces. The system of equations produced is compact, has no peculiarities or degeneration, all variables are simple in their geometric sense. Relationships are presented which connect the variables of the equations produced to the position and velocity of the satellite in a nonmoving Cartesian coordinate system.

SLIPPING MODES OF THE SECOND KIND IN PROBLEMS OF OPTIMAL CONTROL OF THE ROTATION OF A SPACECRAFT, K. G. Grigor'yev, A. M. Nikulin and Yu. B. Popov, p. 235

Many optimal modes produced in problems of orientation of spacecraft from the standpoint of the L. S. Pontryagin maximum principle are particular "cyclically slipping modes (slipping modes of the second kind)" and in the process of solution of the problem can be easily omitted. The presence in the solutions of these variational problems of sectors of "slipping" is a basic peculiarity of these solutions. Therefore, there is definite interest in an investigation of this

type of problem. The present work studies slipping modes of the second kind arriving upon stabilization of space vehicles such as the Skylab.

OPTIMIZATION OF THE PLAN OF A CLOSED PILOTED FLIGHT OF A VEHICLE WITH AN ENGINE OF LIMITED POWER, Yu. A. Zakharov and M. S. Konstantinov, p. 241

This work is dedicated to the problem of optimal planning of a manned spacecraft with a low-thrust engine. In order to create an artificial force of gravity, the vehicle is made to rotate about its center of mass. A new statement is suggested for the basic problem of space flight mechanics with low-thrust engines -- the problem of determining the conditions of delivery of the maximum payload, allowing rotation of the vehicle to be considered, and it is separated into gravimetric and dynamic parts. A method is presented for solving the problem of optimal planning of a manned spacecraft with low thrust, completing a closed interplanetary flight. An Earth-Mars-Earth flight is studied as an example.

THE WORKS OF F. A. TSANDER IN THE AREA OF THE CREATION OF SPACE LIFE SUPPORT SYSTEMS, G. I. Morozov, p. 254

Based on analysis of Archive documents, information is presented on the studies of F. A. Tsander concerning life support systems. The essence and significance of the experiments of F. A. Tsander with higher plants for the creation of such systems is demonstrated.

DEVELOPMENT OF THE IDEAS OF F. A. TSANDER IN THE AREA OF CREATION OF "AVIATION-WEIGHT GREENHOUSES," V. N. Golobin, V. G. Chuchkin, K. S. Arbuzova and S. Ye., Legkov, p. 258 /206

The basic achievements of F. A. Tsander in the area of development of the engineering aspects of the creation of space greenhouses are evaluated. The priority of F. A. Tsander in the development of a number of new methods of growing of plants, particularly aeroponics, is demonstrated. Theoretical estimates and results of experiments on the creation of effective greenhouses intended for long space flights are presented.

THE DEVELOPMENT OF THE IDEAS OF F. A. TSANDER IN THE AREA OF PROTECTION OF SPACECRAFT FROM ENVIRONMENTAL FACTORS, I. M. Korovin, p. 263

A study is made of the basic ideas of F. A. Tsander on the effects of certain space flight factors. The priority

and originality of the suggestions of F. A. Tsander concerning the principles of construction of meteoroid protection systems are demonstrated. The development of the suggestions of F. A. Tsander is traced and characteristics of the current state and prospects for development of radiation and meteoroid protection of spacecraft are given.

SOME INFORMATION ON THE WRITINGS OF F. A. TSANDER CONCERNING PROBLEMS OF LIFE SUPPORT IN SPACE FLIGHT, G. I. Morozov, p. 271

The basic trends in the work of F. A. Tsander on physical-chemical and biological life support systems are demonstrated. An attempt is made at comparative analysis of the chronological sequence of the shorthand manuscripts of F. A. Tsander on life support systems with known events in his biography and creative activity. The intensity and variety of the studies of F. A. Tsander on problems of life support in space flight are illustrated.